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Wakata et al.

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[45] Date of Patent: Jul. 14, 1992

[54] LASER DEVICE WITH OSCILLATION WAVELENGTH CONTROL

[75] Inventors: Hitoshi Wakata; Atsushi Sugitatsu, both of Amagasaki, Japan

[73] Assignee: Mitsubhiski Denki Kabushiki Kaisha, Tokyo, Japan

[21] Appl. No.: 658,475

[22] Filed: Feb. 20, 1991

[30] Foreign Application Priority Data

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Jun. 6, 1990 [JP] Japan 2-147935
Oct. 11, 1990 [JP] Japan 2-274083

[51] Int. Cl.[5] H01S 3/13

[52] U.S. Cl. 372/32; 372/38; 372/108

[58] Field of Search 372/32, 29, 38, 33, 372/108, 98

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Primary Examiner—Léon Scott, Jr.
Attorney, Agent, or Firm—Rothwell, Figg, Ernst & Kurz

[57] ABSTRACT

Laser devices including a rough and a fine adjustment etalons are controlled for wavelength stabilization. Further, a power monitoring mechanism may be provided for measuring the output power of the laser beam, and the rough adjustment etalon is selectively controlled in response to the power monitoring mechanism or to the calculation means. Alternatively, a separate light source oscillating at a wavelength different from the oscillation wavelength of the laser resonator emits light which is split into two parts by a beam splitter. The beams of light emitted from the light source and reflected by the rough adjustment etalon are received by a pair of photosensors, and the rough adjustment etalon is controlled so as to minimize the differential output of the two photosensors.

9 Claims, 16 Drawing Sheets

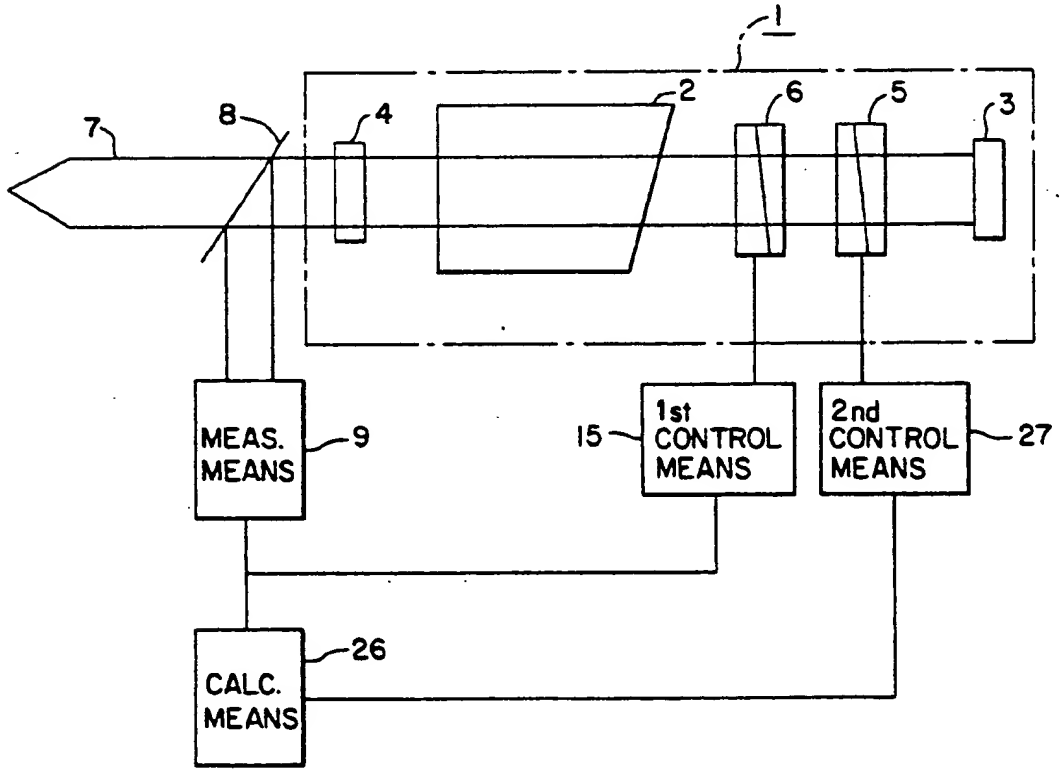


FIG. 1
PRIOR ART

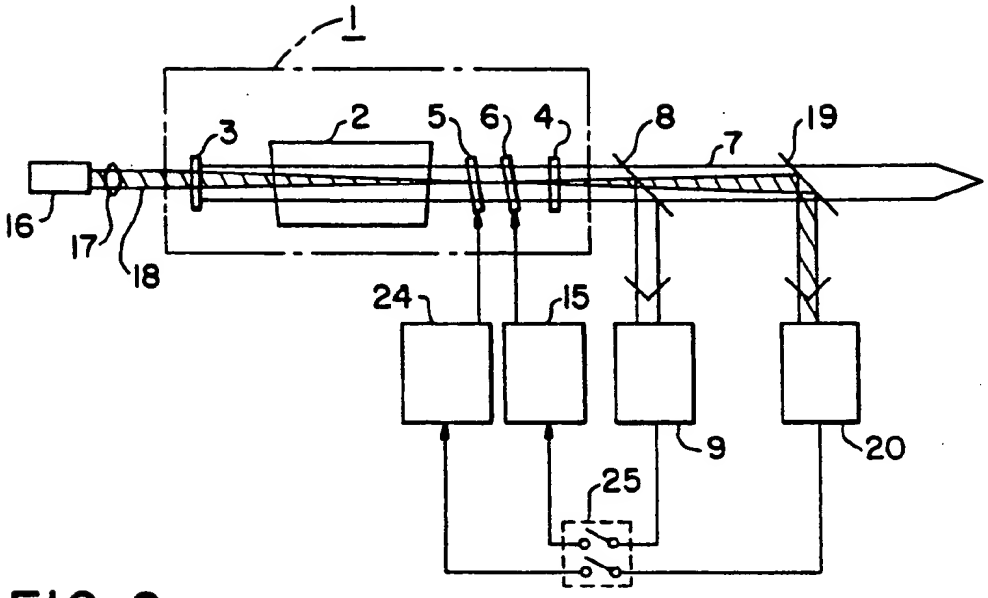


FIG. 2
PRIOR ART

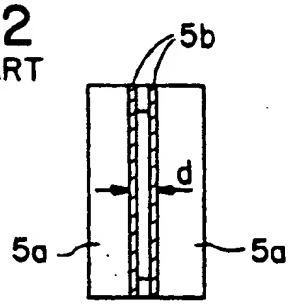


FIG. 3
PRIOR ART

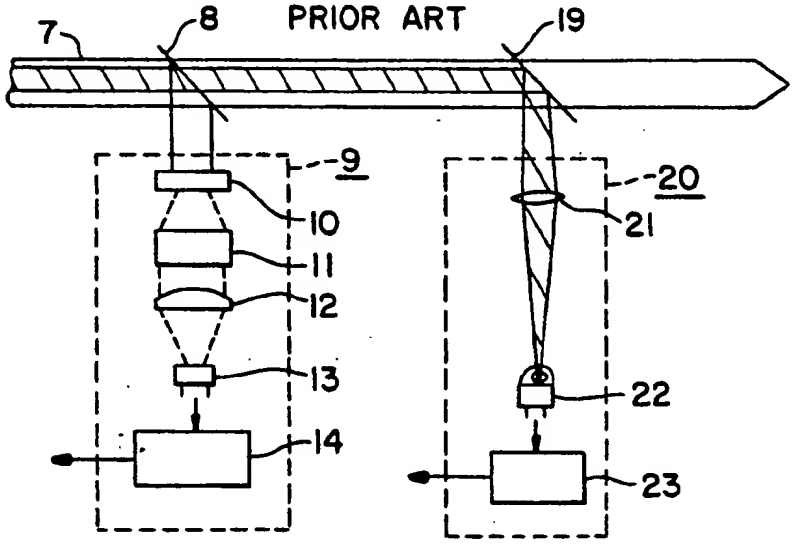


FIG. 4a
PRIOR ART

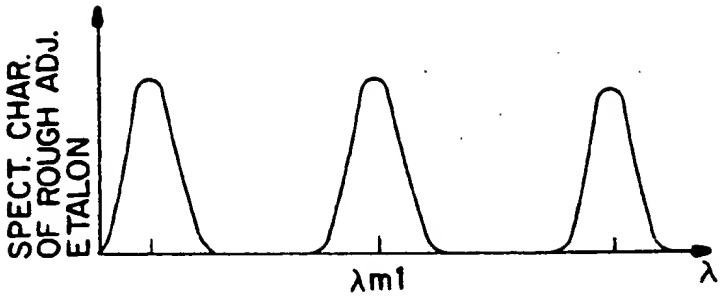


FIG. 4b
PRIOR ART

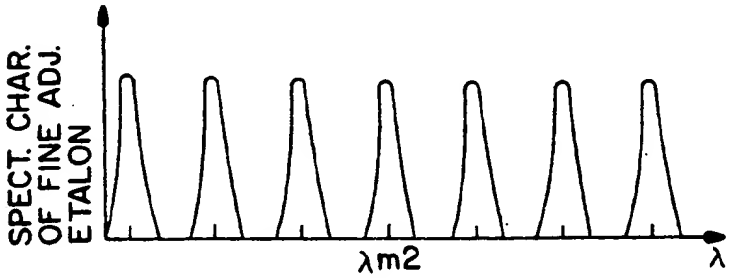


FIG. 4c
PRIOR ART

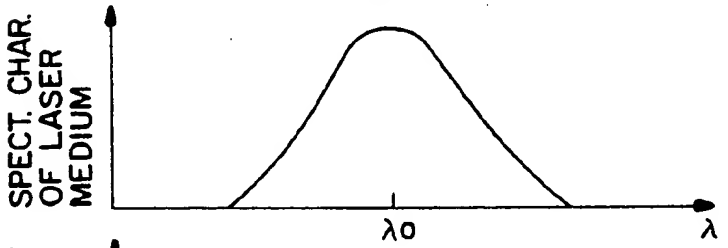


FIG. 4d
PRIOR ART

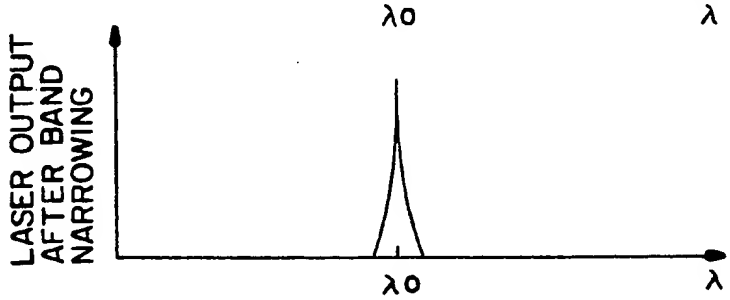


FIG. 5
PRIOR ART

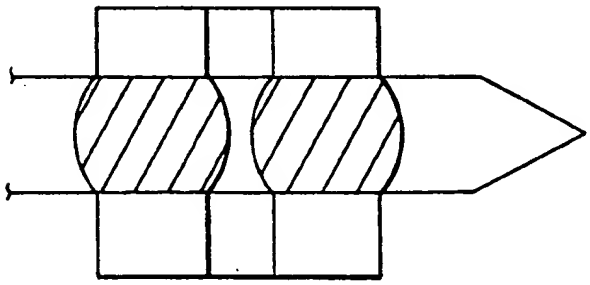


FIG. 6a
PRIOR ART

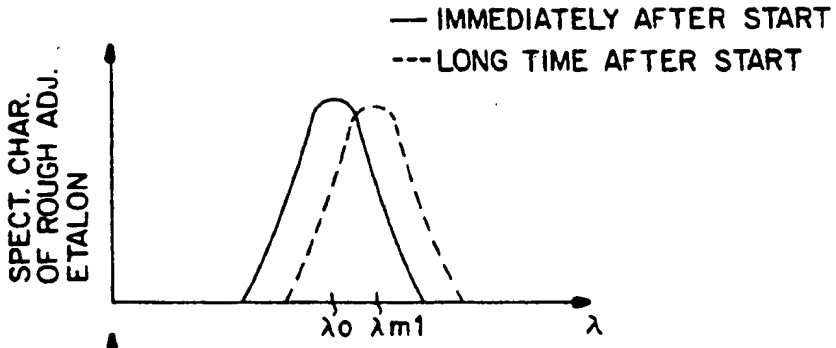


FIG. 6b
PRIOR ART

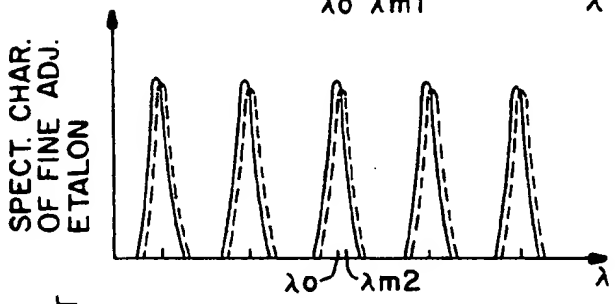


FIG. 6c
PRIOR ART

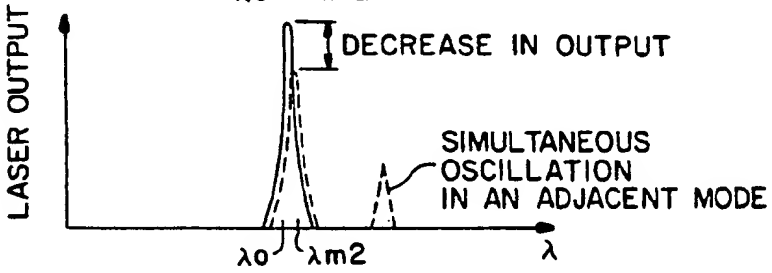


FIG. 7
PRIOR ART

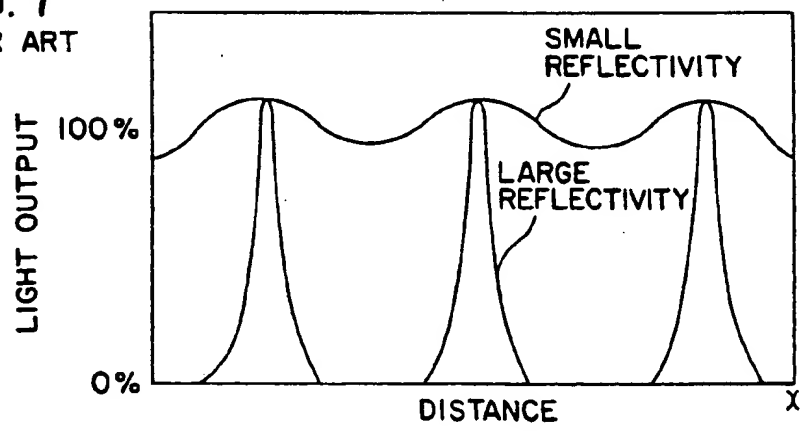


FIG. 8

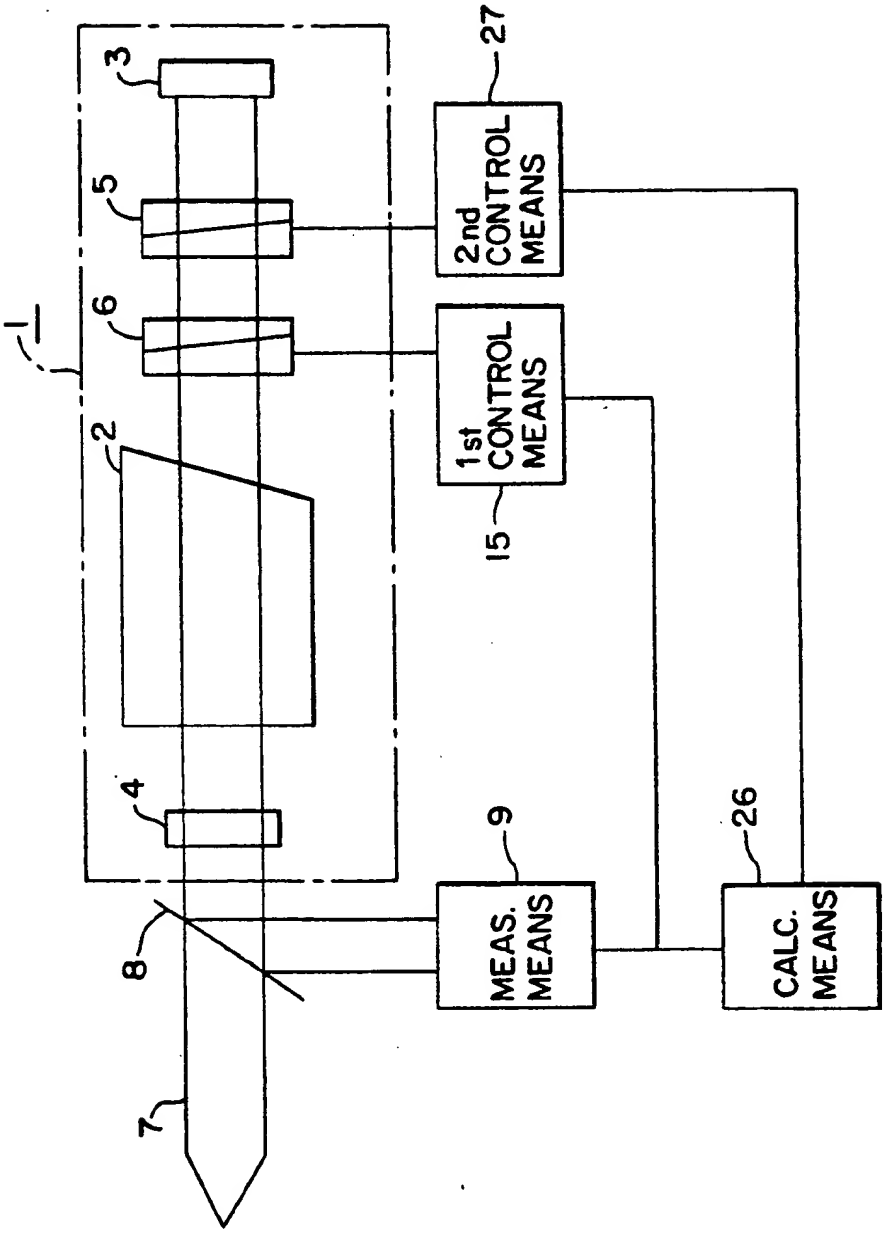

1
2
3
4
5
6
7
8
9
15
26
27
2nd CONTROL MEANS
1st CONTROL MEANS
MEAS. MEANS
CALC. MEANS

FIG. 9

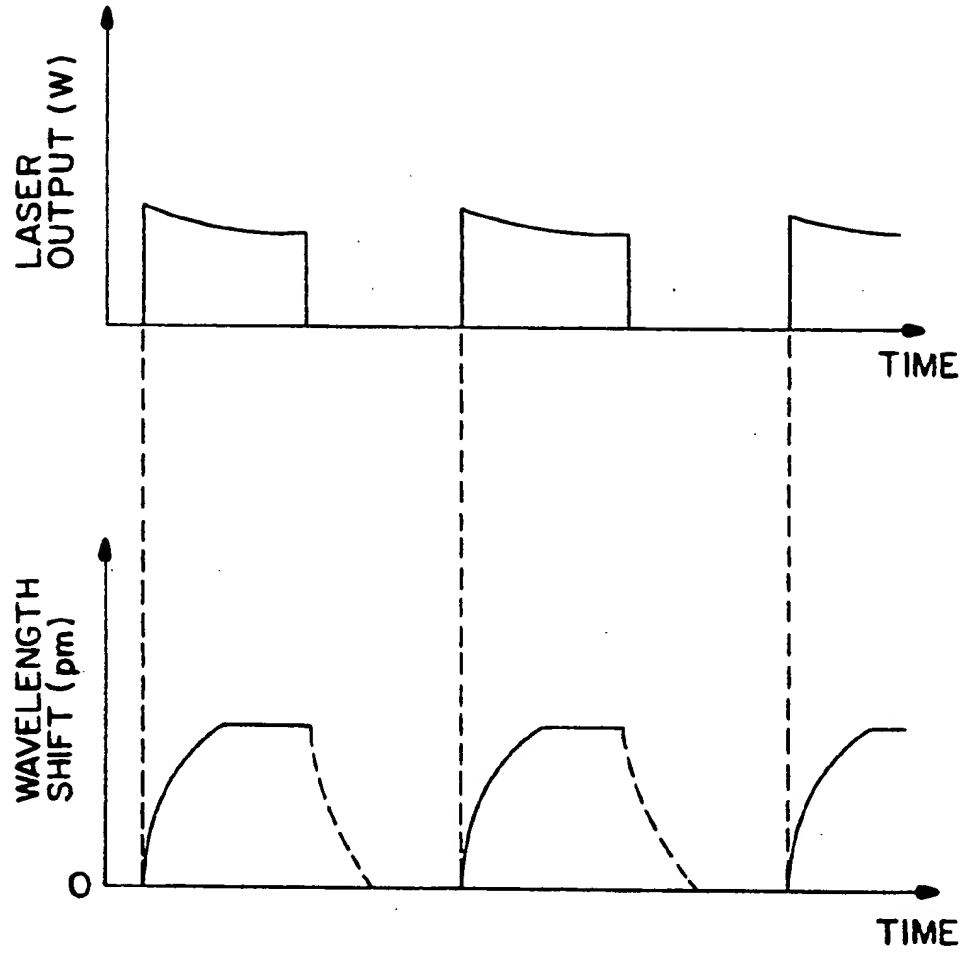


FIG. 10

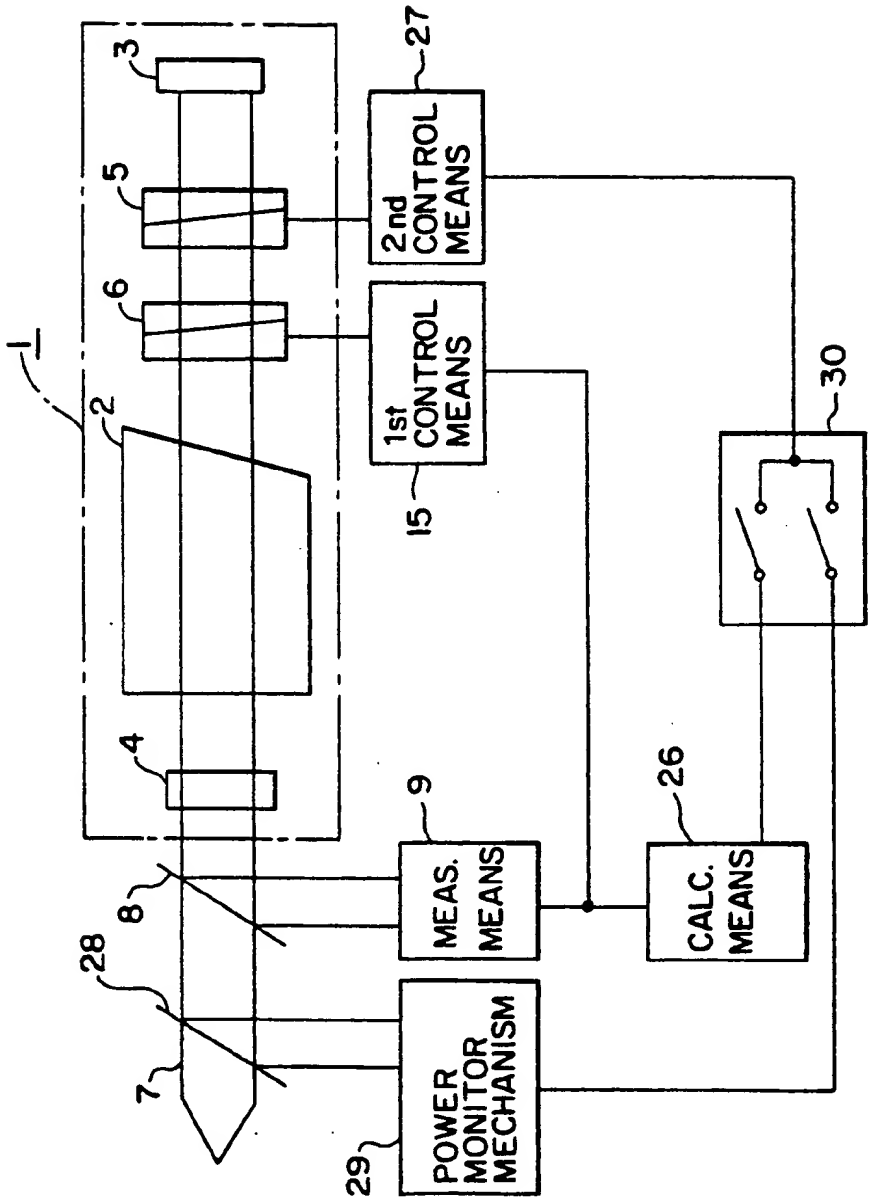

1
2
3
4
5
6
7
8
9
15
26
27
28
29
30
2nd CONTROL MEANS
1st CONTROL MEANS
MEAS. MEANS
CALC. MEANS
POWER MONITOR MECHANISM

FIG. 11

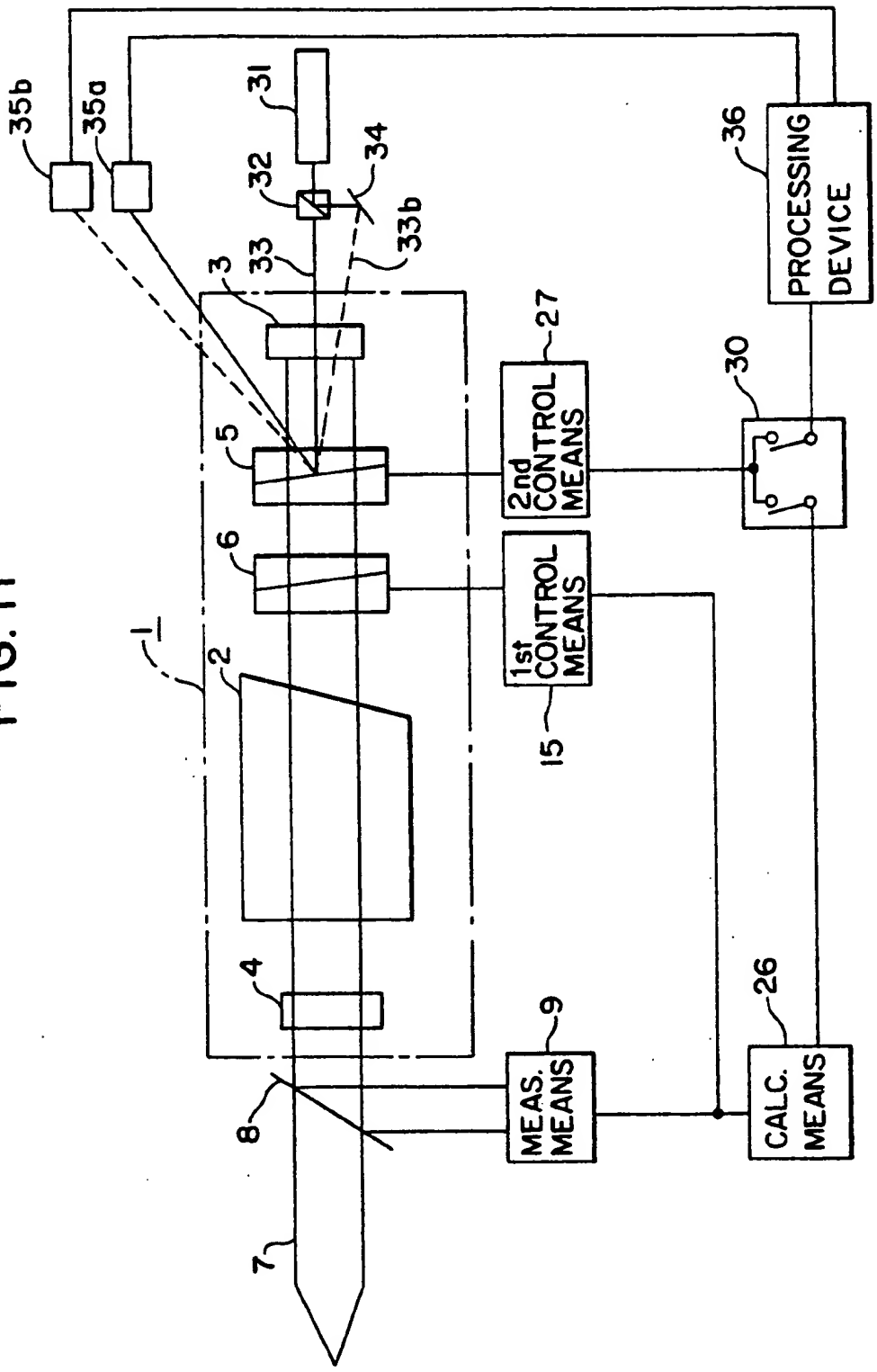

35b
35a
31
32
34
33b
33
3
36
PROCESSING DEVICE
27
2nd CONTROL MEANS
30
5
6
1st CONTROL MEANS
15
1
2
4
9
26
MEAS. MEANS
CALC. MEANS
8
7

FIG. 12

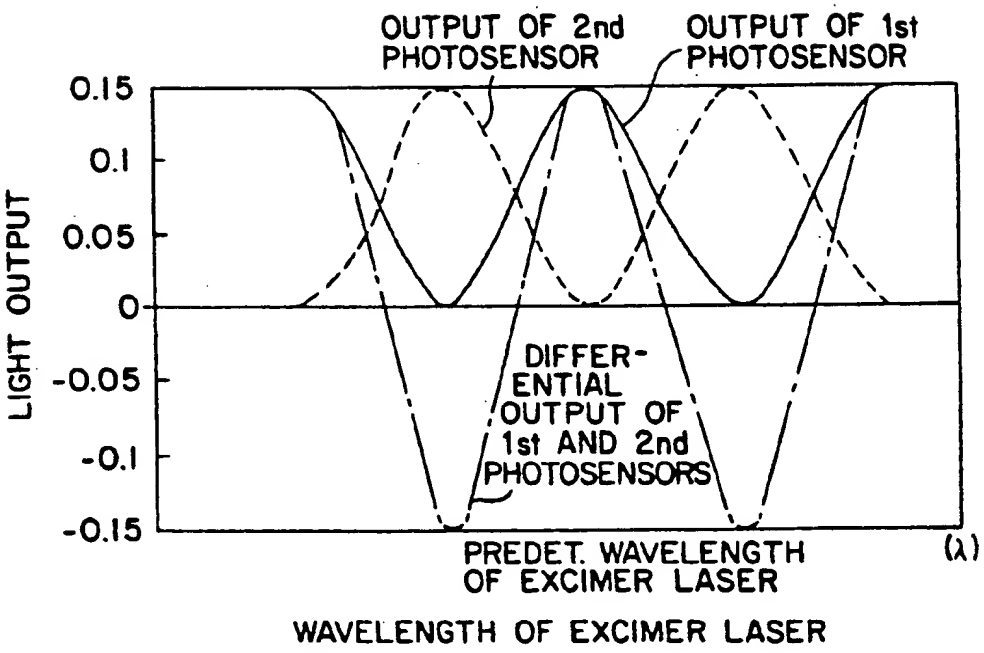

OUTPUT OF 2nd PHOTOSENSOR
OUTPUT OF 1st PHOTOSENSOR
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
LIGHT OUTPUT
DIFFER-ENTIAL OUTPUT OF 1st AND 2nd PHOTOSENSORS
PREDET. WAVELENGTH OF EXCIMER LASER
(λ)
WAVELENGTH OF EXCIMER LASER

FIG. 13a

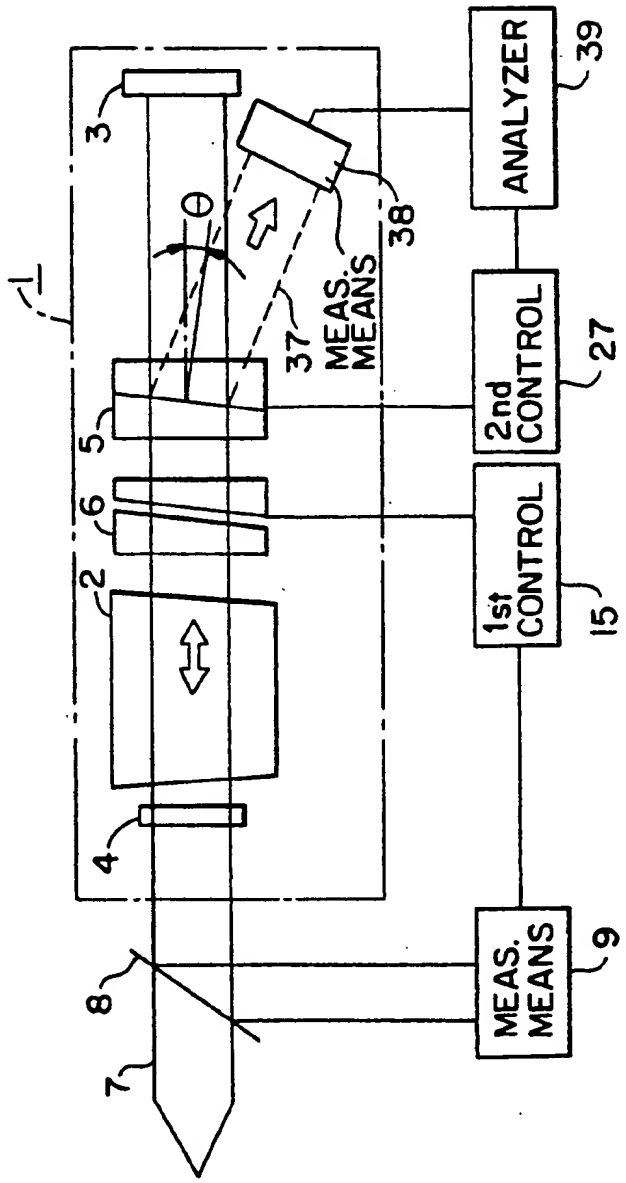


FIG. 13b

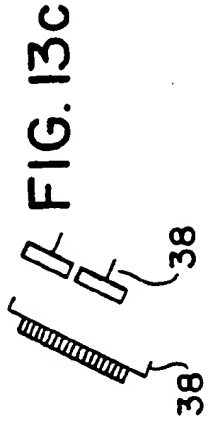


FIG. 13c

FIG. 14

(VAR. OF REFLECTED LIGHT INTENSITY)

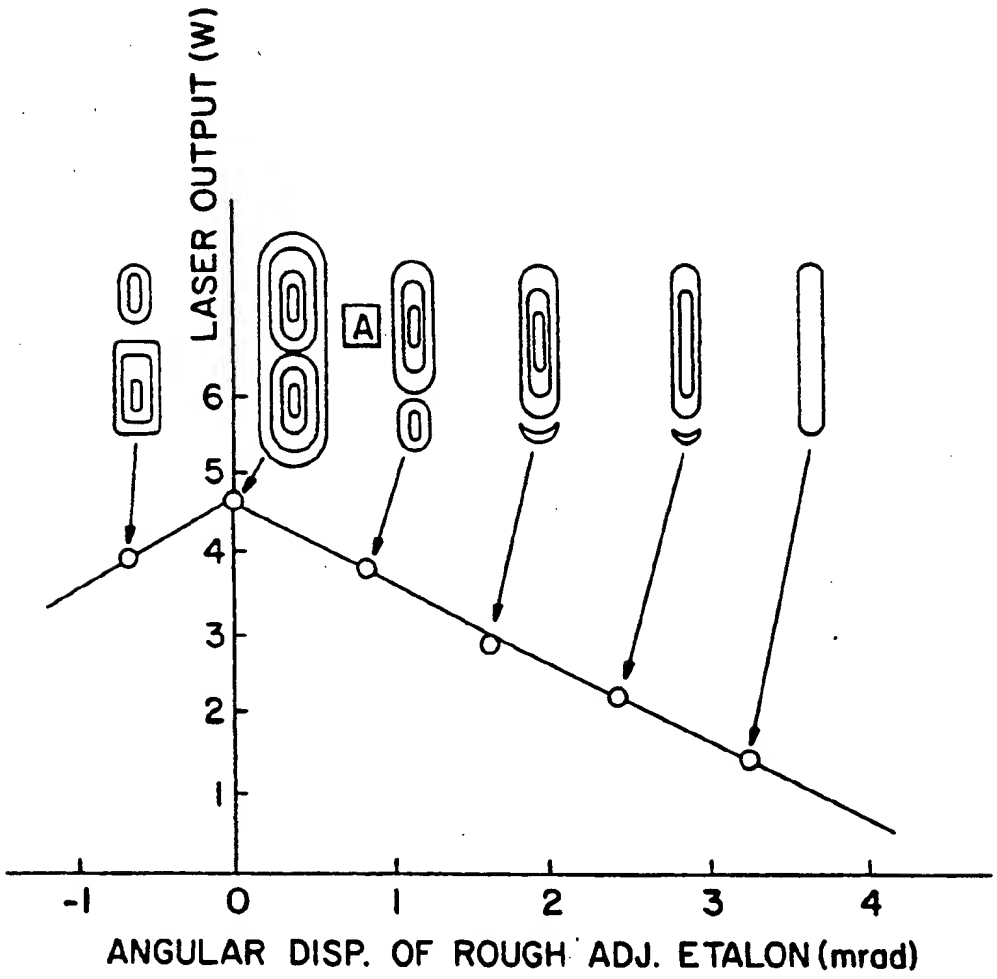


FIG. 15

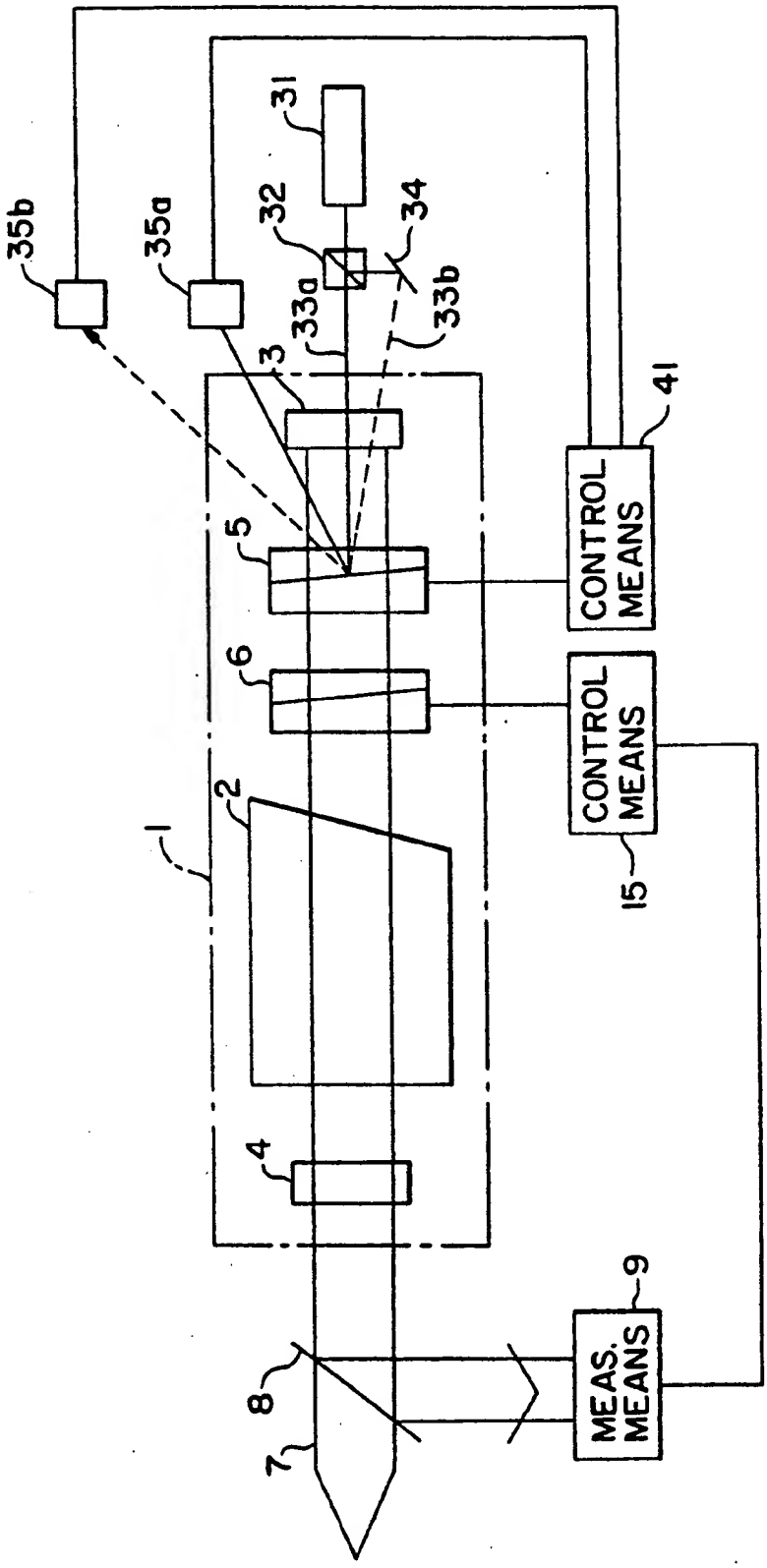

31
32
34
35b
35a
33a
33b
3
41
5
CONTROL MEANS
6
CONTROL MEANS
2
1
15
4
9
MEAS. MEANS
8
7

FIG. 16

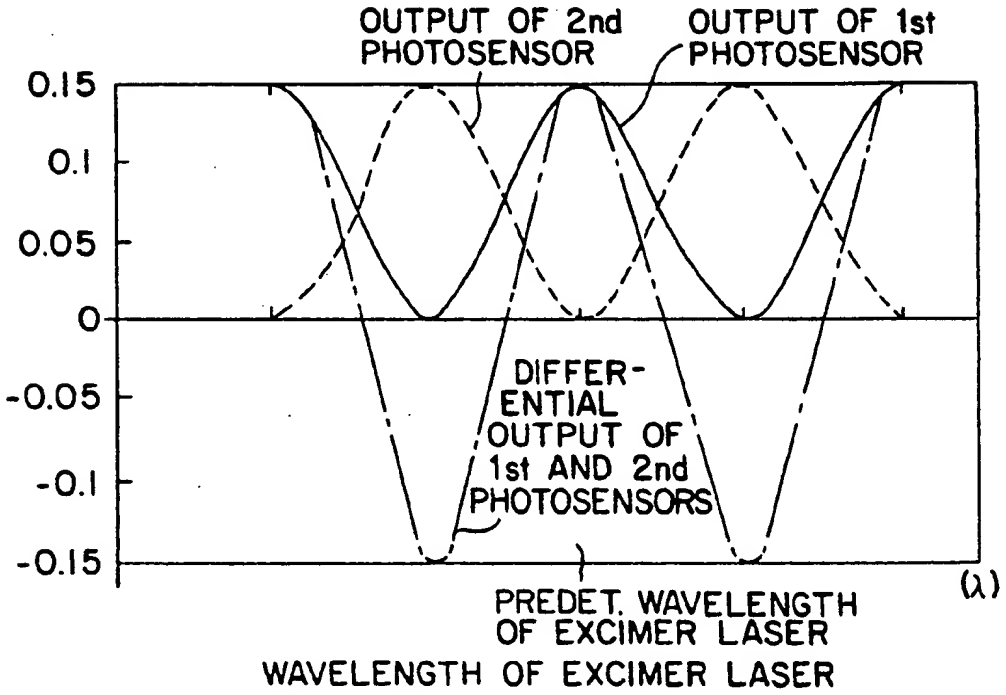

OUTPUT OF 2nd PHOTOSENSOR
OUTPUT OF 1st PHOTOSENSOR
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
DIFFER-ENTIAL OUTPUT OF 1st AND 2nd PHOTOSENSORS
PREDET. WAVELENGTH OF EXCIMER LASER
(λ)
WAVELENGTH OF EXCIMER LASER

FIG. 17

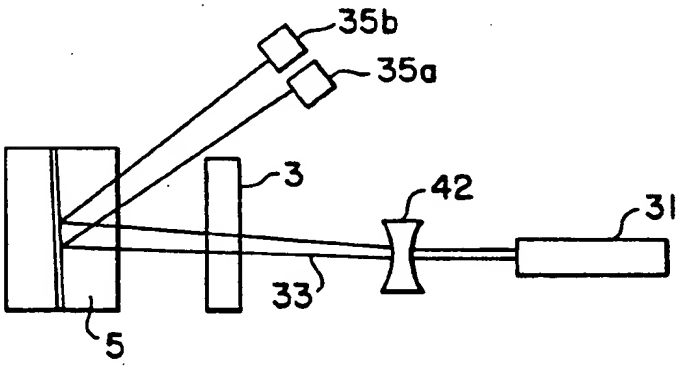

35b
35a
3
42
31
33
5

FIG. 19

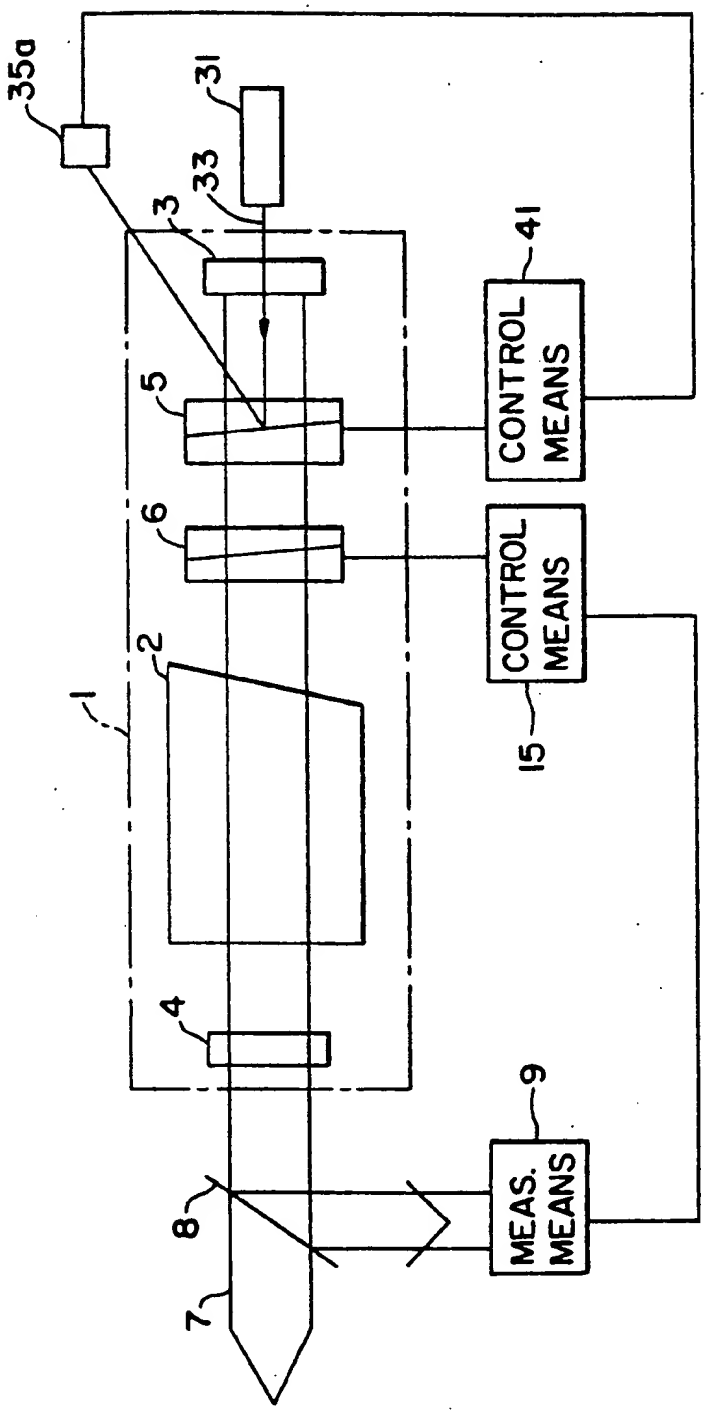

35a
31
33
3
41
CONTROL MEANS
5
6
CONTROL MEANS
2
1
15
4
9
MEAS. MEANS
8
7

FIG. 18

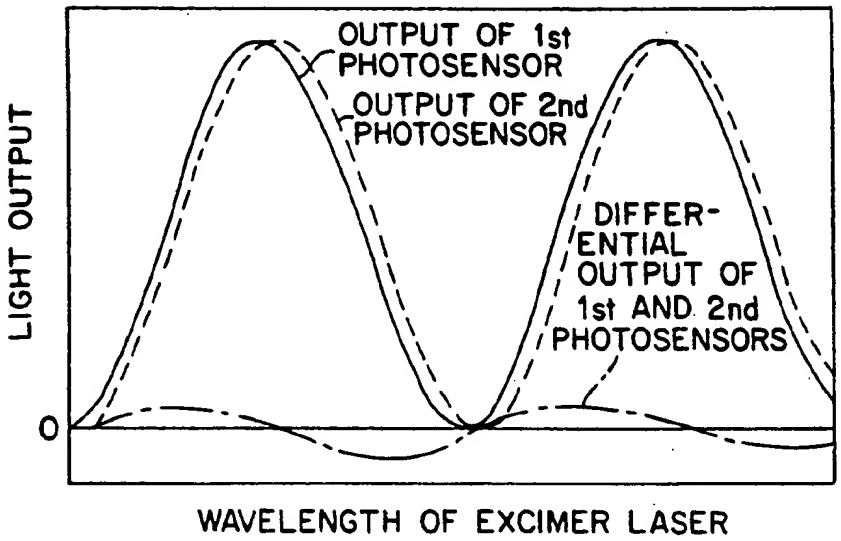

OUTPUT OF 1st PHOTOSENSOR
OUTPUT OF 2nd PHOTOSENSOR
DIFFER-ENTIAL OUTPUT OF 1st AND 2nd PHOTOSENSORS
LIGHT OUTPUT
0
WAVELENGTH OF EXCIMER LASER

FIG. 20

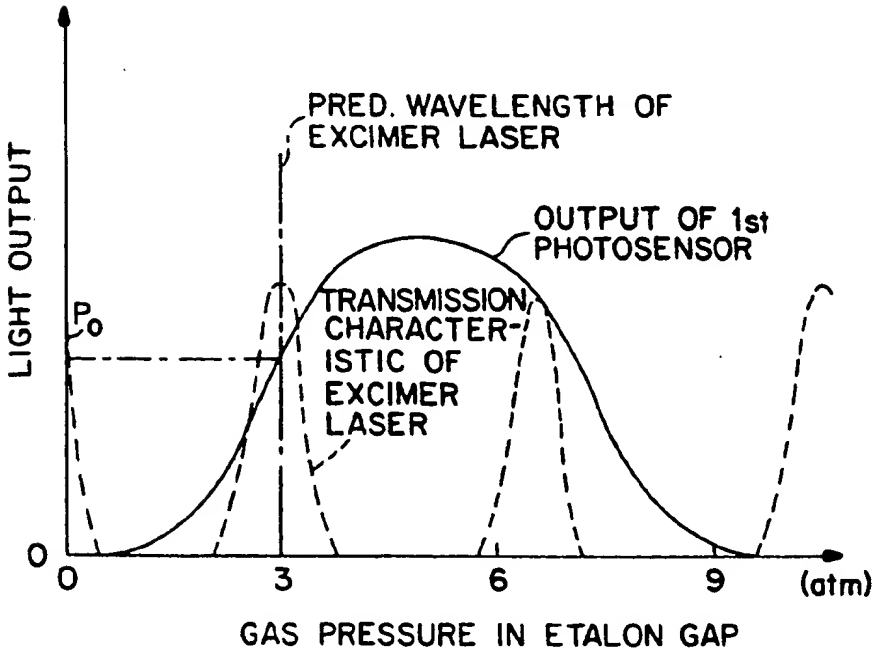

PRED. WAVELENGTH OF EXCIMER LASER
OUTPUT OF 1st PHOTOSENSOR
TRANSMISSION CHARACTER-ISTIC OF EXCIMER LASER
P_o
LIGHT OUTPUT
0
0
3
6
9
(atm)
GAS PRESSURE IN ETALON GAP

FIG. 21

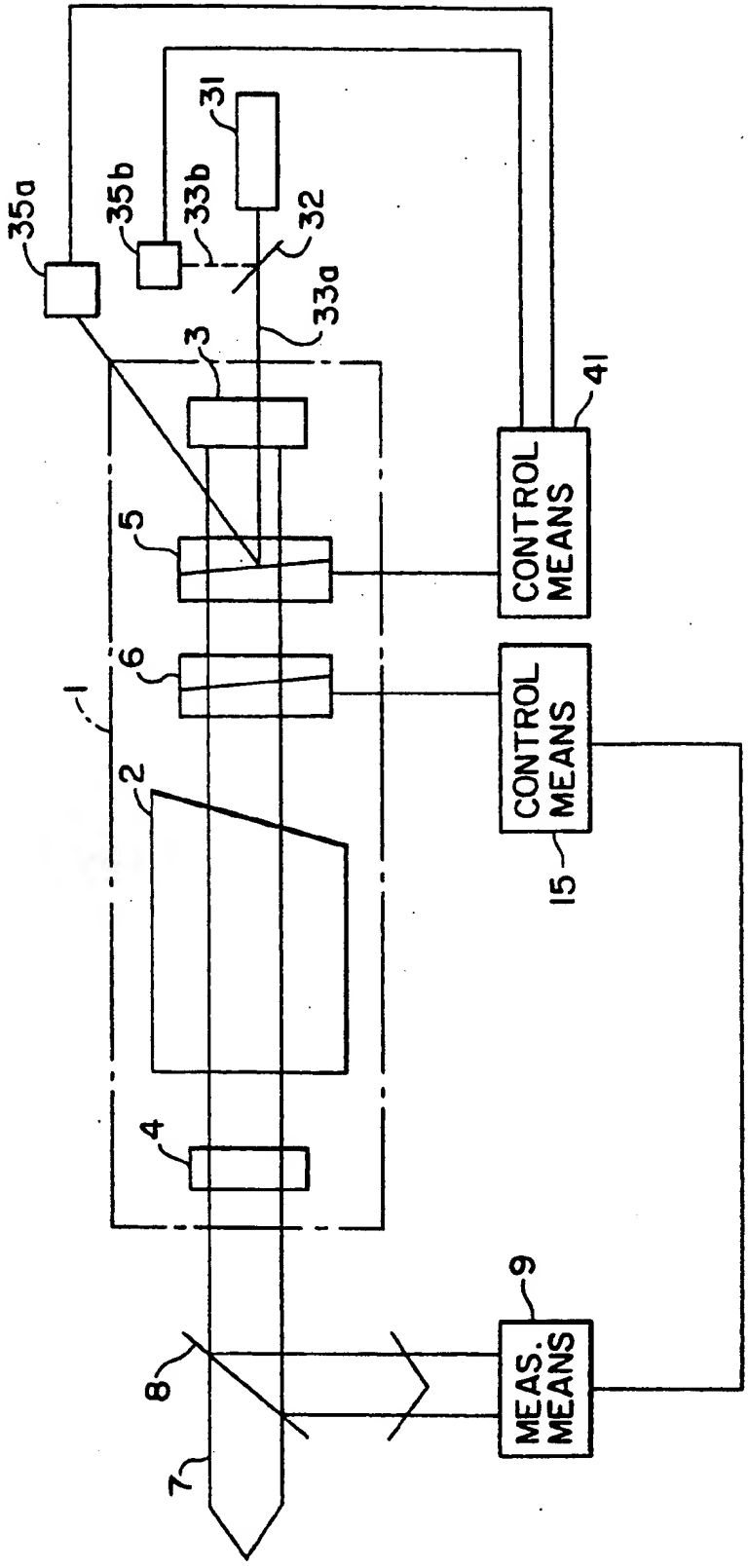
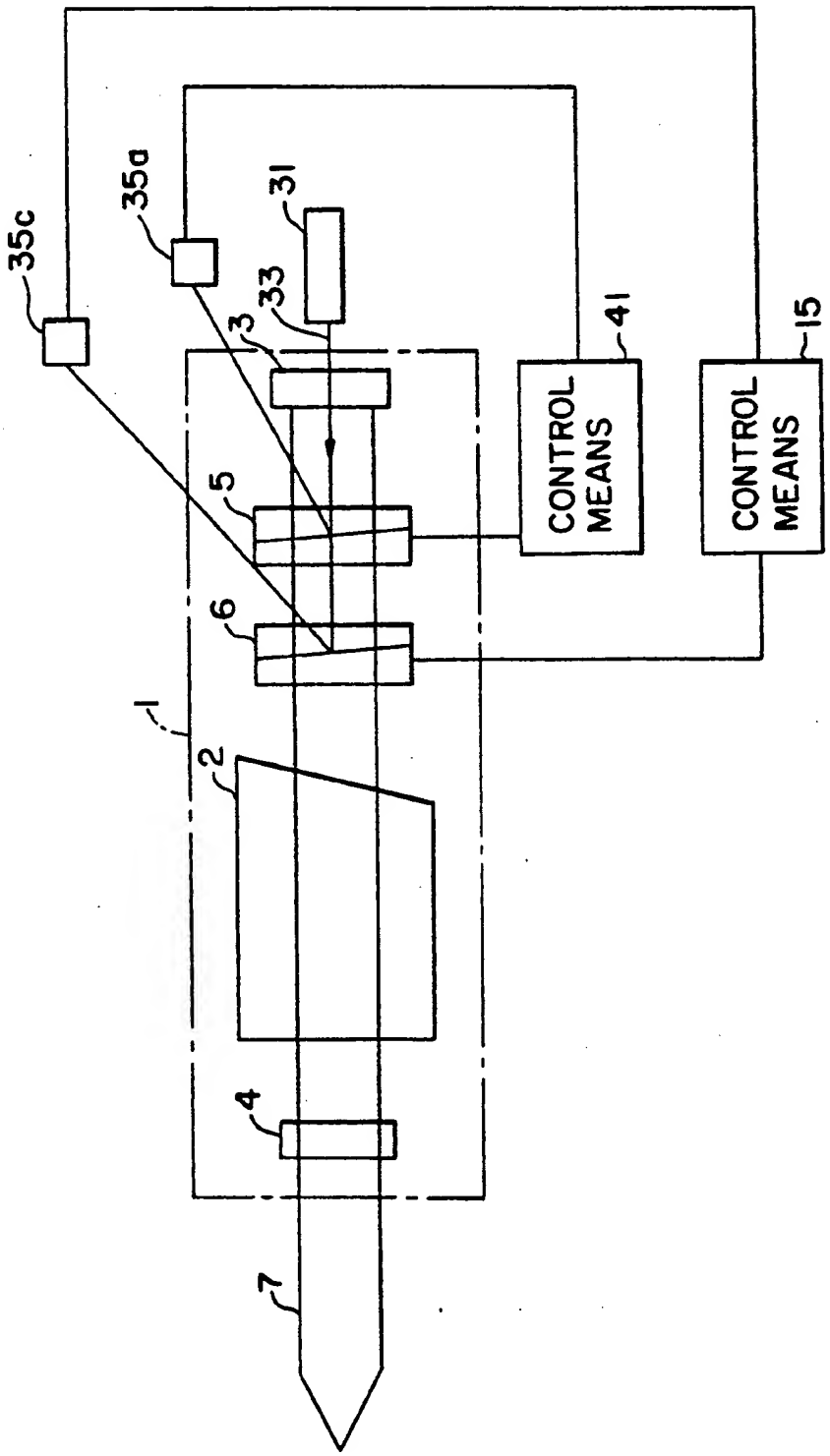

35a
35b
33b
31
32
33a
3
41
5
CONTROL MEANS
6
1
2
CONTROL MEANS
15
4
9
8
MEAS. MEANS
7

FIG. 22



LASER DEVICE WITH OSCILLATION WAVELENGTH CONTROL

BACKGROUND OF THE INVENTION

This invention relates to laser devices, and more particularly to mechanism for stabilizing the oscillation wavelength of the laser beams of laser devices.

Laser devices such as excimer lasers and some of the solid state lasers including semiconductor lasers have relatively wide oscillation bandwidths. Thus, when laser beams of such laser devices are utilized for fine machining, etc., the chromatic aberrations generated by converging lenses cause problems. It has therefore been proposed to insert etalons within the laser resonator of the laser device so as to narrow the bandwidth of the laser beam and obtain a substantially monochromatic laser beam.

FIG. 1 shows such a laser device which is disclosed, for example, in Japanese Laid-Open Patent Application (Kohai) No. 1-205488. A laser resonator 1 consists of a laser medium 2, a totally reflective mirror 3, and a partially reflective mirror 4. Within the laser resonator 1 there are disposed a rough adjustment etalon 5 which roughly selects and narrows the bandwidth of the laser beam, and a fine adjustment etalon 6 which further narrows and determines the wavelength of the laser beam. As shown in FIG. 2, each of these etalons comprises a pair of parallel transparent plates 5*a* opposing each other across a gap d. A reflective coating 5*b* is formed on the opposing surface of each of the plates 5*a*. The central transmission wavelength of the etalons can be adjusted by changing the gap d between the plates 5*a* or the angle of the etalons with respect to the laser beam. The laser beam 7 is outputted from the laser resonator 1 after being narrowed in bandwidth via the rough adjustment etalon 5 and fine adjustment etalon 6. A first interference fringe detector 9 detects the interference fringes formed by the laser beam 7 reflected by the partially reflective mirror 8. As shown in FIG. 3, the first interference fringe detector 9 comprises: an integrator 10 for weakening and diffusing the light for forming the interference fringes, an etalon 11, a lens 12, an imaging element 13 for detecting the positions where the light concentrates, and an image processing unit 14. A first etalon control mechanism 15 adjusts the transmission wavelength of the fine adjustment etalon 6 by changing the gap length d or the angle of the fine adjustment etalon 6 so as to adjust the interference fringes to the predetermined interference fringe pattern of a laser beam having a predetermined oscillation wavelength.

A light source 16 emits light the bandwidth of which is narrowed only by means of the rough adjustment etalon 5. The light pencil 18 emitted from the light source 16 is converged by a converging lens 17 and goes through the rough adjustment etalon 5 to be narrowed in its bandwidth. A second interference fringe detector 20 detects the interference fringes formed by the light pencil 18 emitted from the light source 16 after transmitting through the rough adjustment etalon 5 and reflecting at the reflection mirror 19. As shown in FIG. 3, the second interference fringe detector 20 comprises a lens 21 for forming the interference fringes, an imaging element 22 for detecting the positions where the light is concentrated, and an image processing unit 23. The interference fringes formed on the imaging element 22 within the second interference fringe detector 20 are

generated by the light 18 the bandwidth of which is narrowed only via the rough adjustment etalon 5. A second etalon control mechanism 24 controls and changes the transmission wavelength of the rough adjustment etalon 5 by adjusting the gap length d or the angle of the rough adjustment etalon 5 such that the interference fringes form in the second interference fringe detector 20 are adjusted to the interference fringe pattern corresponding to a predetermined oscillation frequency of a laser beam. A selection control mechanism 25 determines whether it is necessary to control the rough adjustment etalon 5 and fine adjustment etalon 6, and when it is necessary, judges the priority of the control thereof.

The method of operation of the laser device is as follows. The light generated in the laser medium 2 bounces back and forth between the totally reflective mirror 3 and partially reflective mirror 4 and thus is amplified within the laser resonator 1. The amplified light goes out of the laser resonator 1 as the laser beam 7. Since the rough adjustment etalon 5 and fine adjustment etalon 6 are inserted within the laser resonator 1, the oscillation bandwidth is narrowed, and hence a substantially monochromatic laser beam 7 can be obtained.

The principle of bandwidth narrowing by means of the rough adjustment etalon 5 and fine adjustment etalon 6 is as follows. FIG. 4 shows the principle by which the oscillation bandwidth of laser beam is narrowed. FIG. 4(*a*) shows the spectral transmission characteristic of the rough adjustment etalon 5. The central transmission wavelength λm_1 are given by the following equation (1)

$$\lambda m_1 = 2\, n_1 d_1 \cos\theta_1 / m_1 \tag{1}$$

wherein:

n_1 represents the reflectivity of the material filling the space between the two mirror surfaces of the etalon;

d_1 represents the distance between the two mirror surfaces of the etalon;

θ_1 represents the incident angle of the laser beam on etalon; and

m_1 is an integer whose distinct values correspond to the respective transmission peaks of the etalon.

As can be clearly seen from this equation, the wavelengths at the transmission peaks can readily be adjusted at will by changing the values of n_1, d_1, and θ_1. On the other hand, the region between the transmission peaks are known as free spectral regions (FSR), which are given by the following equation (2):

$$FSR_1 = \lambda m_1^2 / 2 n_1 d_1 \cos\theta_1 \tag{2}$$

Further, the half value width of the transmission peaks $\Delta\lambda_1$ is given by the following equation (3):

$$\Delta\lambda_1 = FSR_1 / F_1 \tag{3}$$

where F_1 is a value known as finesse which is determined by the performance of the etalon.

On the other hand, FIG. 4(*c*) shows the spectroscopic characteristic of the gain of the laser medium 2. If the etalons are not disposed within the laser resonator 1, the light is amplified in the bandwidth range where the gain is present, and hence a laser beam of wide oscillation bandwidth is generated. There is inserted, however, the rough adjustment etalon 5, and the parameters (such as

d_1) of the rough adjustment etalon **5** are selected such that one and only one transmission peak position λm_1 of the rough adjustment etalon **5** is within the gain region of the laser medium **2**. In the case shown in the figure, the peak transmission wavelength λm_1 of the rough adjustment etalon **5** is at the central wavelength λ_0 of the gain of the laser medium **2**, and the adjacent transmission peaks are outside of the gain region of the laser medium **2**. Thus, the attenuation due to the rough adjustment etalon **5** is small only in the neighborhood of the central wavelength λ_0, and the light is amplified only near at λ_0, thereby generating a laser beam narrowed in its oscillation bandwidth.

In order to limit the number of the transmission peaks present within the gain region to one, the free spectral region FSR_1 must be greater than a minimum determined by the width of the gain region of the laser medium **2**. On the other hand, the finesse F_1, which is determined by the performance of etalon, is about 20 at most. Thus, the narrowing of bandwidth by means of rough adjustment etalon **5** alone has its limit. Thus, another etalon, fine adjustment etalon **6**, is utilized. The spectroscopic transmission characteristic of the fine adjustment etalon **6** is shown in FIG. **4**(*b*). A peak transmission wavelength λm_2 thereof is turned at the central wavelength λ_1 of the laser medium **2**, and the free spectral region FSR_2 thereof is selected at a value greater than $\Delta\lambda_1$ ($FSR_2 > \Delta\lambda_1$).

Thus, the laser bean, generated by the laser medium **2** and having the spectroscopic characteristic as shown in FIG. **4**(*c*), is narrowed in oscillation bandwidth, as shown in FIG. **4**(*d*), to a narrow band around the central wavelength λ_0 at which the transmission peaks of the rough adjustment etalon **5** and fine adjustment etalon **6** overlap each other. Since, the light goes back and forth many times through the etalons, the bandwidth of the laser beam is narrowed to from one half to tenth (½ to 1/10) of the bandwidth as determined by the transmission characteristics of the two etalons.

Where it is desirable to further reduce the bandwidth of the laser beam, another etalon may be inserted within the laser resonator **1**.

The oscillation bandwidth of the laser beam can be narrowed as described above. When, however, the laser beam goes back and forth through the etalons in oscillation, heat is generated in the etalons, and, as a result, the etalons are deformed as shown in FIG. **5**. These thermal deformations of the etalons, while not so severe as to deteriorate the performance characteristics of the etalons, do change the gap length d of the etalons, and thereby shift the central transmission wavelength thereof. The circumstance is shown in FIG. **6**. FIG. **6**(*a*) shows the spectroscopic transmission characteristic of the rough adjustment etalon **5**, where the solid curve represents the characteristic immediately after the start of the oscillation, and the dotted curve represents the shifted characteristic after etalon has been heated. The relation between the shift of the transmission peak $\Delta\lambda$ and the variation Δd of the gap d is given by the following equation (**4**):

$$\Delta\lambda = (\lambda m/d)\,\Delta d \qquad (4)$$

Incidentally, the direction of the shift of wavelength is determined by the structure of the etalon. With respect to a particular etalon, the peak transmission wavelength is shifted in a certain direction due to the thermal deformation caused by the laser beam.

Not only the peak transmission wavelength of the rough adjustment etalon **5**, but also that of the fine adjustment etalon **6** is shifted as shown by the dotted curve in FIG. **6**(*b*). The gap length of the fine adjustment etalon **6**, however, is greater than that of the rough adjustment etalon **5**, such that the transmission wavelength shift of the fine adjustment etalon **6** is smaller than that of the rough adjustment etalon **5**. Thus, central peak transmission wavelengths λm_1 and λm_2 of the etalons **5** and **6** become separated from each other. The overall transmission characteristic of the two etalons **5** and **6** superposed on each other is therefore reduced, as shown in FIG. **6**(*c*), compared with the case where the central transmission wavelengths λm_1 and λm_2 are equal to each other. Thus, after a long time subsequent the start of oscillation, not only the oscillation wavelength of laser beam is shifted from λ_0 to λm_2, but also the output power is decreased. Furthermore, when the wavelength shifts are large, oscillation in another adjacent mode of the fine adjustment etalon **6** may be observed (see FIG. **6**(*c*).

Thus, control is effected to stabilize the oscillation wavelength of the laser beam as follows. Part of the laser beam **7** is guided to the first interference fringe detector **9** via the partially reflective mirror **8** and is diverged by the integrator **10** (see FIG. **3**). Only the components of the light diverged by the integrator **10** having particular incident angles θ to the etalon **11** are transmitted therethrough to reach the lens **12**. When the focal length of the lens **12** is represented by f, the light having the incident angle θ is concentrated at positions separated from the lens axis by a radial distance $f\theta$, and thereby forms a circular interference fringe. The imaging element **13** detects the positions at which the light is concentrated, and the image processing unit **14** analyses the detected result, thereby obtaining the incident angel θ, from which the current oscillation wavelength of the laser beam can be calculated. The oscillation wavelength of the laser beam is determined solely by the transmission characteristic of the fine adjustment etalon **6**. Thus, the fine adjustment etalon **6** is adjusted, via the first etalon control mechanism **15**, with respect to its angle to the laser beam, or its gap length d, such that the central transmission wavelength of the fine adjustment etalon **6** is tuned to the predetermined wavelength. The oscillation of the laser beam is thus adjusted to the predetermined wavelength.

The control of the rough adjustment etalon **5**, on the other hand, is effected as follows. The light emitted from the light source **16** reaches the rough adjustment etalon **5**, and the components having particular incident angles are thereby selected. The light thus elected via the rough adjustment etalon **5** is transmitted through the fine adjustment etalon **6** without further selection. Then, the light is reflected by the reflection mirror **19**, which has a particularly high reflectivity to the light at the wavelength of the light source **16**, and thence is guided to the second interference fringe detector **20**. The light is then converged by the lens **21**, to form circular interference fringes generated by the selection of the light via the rough adjustment etalon **5** (see FIG. **3**). The imaging element **22** detects the positions where the light is concentrated, and the image processing unit **23** analyses the detected result, thereby obtaining the central transmission wavelength of the rough adjustment etalon **5**. The angle or the gap length of the rough adjustment etalon **5** is controlled by means of the second etalon control mechanism **24**, so as to tune the

central transmission wavelength of the rough adjustment etalon 5 to the predetermined wavelength.

The above laser device, however, has the following disadvantage.

FIG. 7 shows the relation between the reflectivity of the rough adjustment etalon 5 and the intensity of the interference fringes. When the reflectivity is small, the variation of the intensity of light is also small and the interference fringes are obscure. Thus, the detection of the interference fringes by the imaging element 22 is difficult, and hence an accurate control of the rough adjustment etalon 5 is difficult to perform.

Thus, in order to perform an accurate control of the rough adjustment etalon 5, the reflectivity of the reflective surface 5*b* of the rough adjustment etalon 5 must be made large enough to ensure a formation of distinct and clear interference fringes in the second interference fringe detector 20. Otherwise, erroneous control may ensue.

On the other hand, increasing the reflectivity of the etalon signifies increasing the number of reflective layers constituting the reflective surface 5*b* of the etalon. This makes the production of the etalon difficult. Further, when the reflectivity increases, the absorption of light also increases. This reduces the resistance of the etalon to the light.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a laser device which is capable of outputting a laser beam stabilized in the output power and oscillation wavelength. In particular, this invention aims at providing laser device in which the central transmission wavelength of the rough adjustment etalon can be controlled stably and reliably to the predetermined wavelength of the laser beam.

The above object is accomplished in accordance with the principle of this invention by a laser device which comprises: a laser resonator including a first and a second etalon having distinct transmission bandwidths, wherein a transmission bandwidth of the first etalon is narrower than a transmission bandwidth of the second etalon; measurement means for measuring an oscillation wavelength of a laser beam outputted from said laser resonator; first control means, coupled to an output of said measurement means, for controlling the first etalon such that the oscillation wavelength of the laser beam detected by the measurement means is adjusted to a predetermined wavelength; calculation means coupled to an output of said measurement means, for calculating a shift of the transmission wavelength of the second etalon in response to a measurement of the oscillation wavelength of the laser beam effected by the measurement means: and second control means, coupled to an output of the calculation means, for controlling the transmission wavelength of the second etalon to the predetermined wavelength in response to the output of the calculation means.

Alternatively, the above object is accomplished by a laser device which comprises: a laser resonator including a first and a second etalon having distinct transmission bandwidths, wherein a transmission bandwidth of the first etalon is narrower than a transmission bandwidth of the second etalon; a light source emitting light on at least one of said etalons; a photosensor means for detecting an intensity of light emitted from said light source and reflected by said one of the etalons; and control means, coupled to an output of said photosensor means, for controlling the transmission wavelength of said one of the etalons to a predetermined wavelength in response to the intensity of light detected by said photosensor means.

BRIEF DESCRIPTION OF THE DRAWINGS

The features which are believed to be characteristic of this invention are set forth in the appended claims. This invention itself, however, may best be understood from the detailed description of the preferred embodiments, taken in connection with the accompanying drawings, in which:

FIG. 1 is a schematic view showing the organization of a conventional laser device including etalons;

FIG. 2 shows the section of a etalon;

FIG. 3 shows the details of the etalon control mechanisms of the laser device of FIG. 1;

FIGS. 4*a*–4*d* shows the spectroscopic characteristics of the various parts of the laser device;

FIG. 5 is a sectional view of an etalon under thermal deformation;

FIGS. 6*a*–6*c* shows the shifts of the spectroscopic characteristics of the etalons, etc., due to thermal deformations thereof;

FIG. 7 shows the relation between the reflectivity of the etalon and the intensity of the interference fringes;

FIG. 8 is a schematic view of an embodiment according to this invention;

FIG. 9 shows the temporal variation of the laser output power and the wavelength shift;

FIG. 10 is a view similar to that of FIG. 8, showing another embodiment according to this invention, which is provided with a power monitoring mechanism;

FIG. 11 is a view similar to that of FIG. 8, showing still another embodiment according to this invention;

FIG. 12 shows the variation, with respect to the wavelength, of the outputs of the photosensors of the laser device of FIG. 11;

FIG. 13 is a view similar to that of FIG. 8, showing still another embodiment according to this invention;

FIG. 14 shows the variations, relative to the tilt of the rough adjustment etalon, of the laser output power and the intensity of the reflected light of the laser device of FIG. 13;

FIG. 15 is a view similar to that of FIG. 8, showing still another embodiment according to this invention;

FIG. 16 shows the variation, with respect to the wavelength, of the outputs of the photosensors of the laser device of FIG. 15;

FIG. 17 shows a modification of the laser device of FIG. 15;

FIG. 18 is a graph showing the variation, with respect to the wavelength, of the outputs of the photosensors of the laser device of FIG. 17;

FIG. 19 is a view similar to that of FIG. 8, showing still another embodiment according to this invention;

FIG. 20 shows the relation between the gas pressure in the etalon and the laser output; and

FIGS. 21 and 22 are views similar to that of FIG. 8, showing further embodiments according to this invention.

In the drawings, like reference numerals represent like or corresponding parts or portions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 8 shows a laser device according to an embodiment of this invention, the fundamental structure of

which is similar to that of FIG. 1. The parts identical or similar to those of the laser device of FIG. 1 are represented by the same reference numerals. Thus, as in the case of the laser device of FIG. 1, the light generated in the laser medium 2 bounces back and forth between the totally reflective mirror 3 and partially reflective mirror 4 and thus is amplified within the laser resonator 1. The amplified light is outputted from the laser resonator 1 as the laser beam 7. Since the rough adjustment etalon 5 and fine adjustment etalon 6 are inserted within the laser resonator 1, the oscillation bandwidth of the laser beam is narrowed, and substantially monochromatic laser beam 7 can be obtained. A calculation means 26 determines the shift of the central transmission wavelength of the rough adjustment etalon 5. This determination is effected on the basis of the shift of the oscillation wavelength of the laser beam relative to the predetermined wavelength, which shift is detected by the first interference fringe detector 9. In accordance with the output of the calculation means 26, a second etalon control mechanism 27 controls the transmission wavelength of the rough adjustment etalon 5 by adjusting the gap length d, the sealing pressure, or the angle θ relative to the laser beam of the rough adjustment etalon 5. Otherwise, the organization is similar to that of the laser device of FIG. 1.

The control of the etalons for the stabilization of the laser beam is effected as follows.

The method of control of the fine adjustment etalon 6 is similar to that of the laser device of FIG. 1. Thus, part of the laser beam 7 is guided to the first interference fringe detector 9 via the partially reflective mirror 8 and is diverged by the integrator 10 (see FIG. 3). Only the diverging components of the integrator 10 having particular incident angles to the etalon 11 are transmitted therethrough to reach the lens 12. When the focal length of the lens 12 is represented by f, the light having the incident angle θ is concentrated at positions separated from the lens axis by a radial distance $f\theta$, and thereby forms a circular interference fringe. The imaging element 13 detects the positions at which the light is concentrated, and the image processing unit 14 analyses the detected results, thereby obtaining the incident angle θ, from which the current oscillation wavelength of the laser beam can be calculated. The oscillation wavelength of the laser beam is determined solely by the transmission characteristic of the fine adjustment etalon 6. Thus, the fine adjustment etalon 6 is adjusted, via the first etalon control mechanism 15, with respect to its angle to the laser beam, or its gap length d, such that the central transmission wavelength of the fine adjustment etalon 6 is tuned to the predetermined wavelength. The oscillation of the laser beam is thus adjusted to the predetermined wavelength.

On the other hand, the control of the rough adjustment etalon 5 is effected as follows. The oscillation wavelength of the laser beam measured by the first interference fringe detector 9 as described above is outputted to the calculation means 26. In response thereto, the calculation means 26 determines the shift of the oscillation wavelength of the laser beam with respect to the predetermined wavelength. The central transmission wavelength of the rough adjustment etalon 5 is calculated by the calculation means 26 from the value of the shift of the central transmission wavelength of the fine adjustment etalon 6 as described in detail hereinbelow. In response to the output of the calculation means 26, the second etalon control mechanism 27 controls the sealing pressure, the gap length d, or the angle relative to the laser beam, of the rough adjustment etalon 5, such that the central transmission wavelength of the rough adjustment etalon 5 is maintained to the predetermined wavelength of laser beam.

The details of the method of control of the rough adjustment etalon 5, in particular the method of operation of the calculation means 26, is as follows.

The inventors have made researches into the relation which holds between the length of output time and the magnitude of shift of the oscillation wavelength of the laser beam relative to the predetermined wavelength. FIG. 9 shows the results of experiments that are conducted for the purpose of clarifying such relation. As shown in FIG. 9, the oscillation wavelength of the laser beam is shifted from the predetermined wavelength according to a predetermined curve after the start of oscillation of the laser beam, and returns to the predetermined wavelength soon after the oscillation is stopped. Wavelength shifts follow a regular pattern and do not take place at random. The wavelength shifts are caused by the thermal deformation of the etalons as shown in FIG. 5. Due to the heat generated by the laser beam going through the etalons, the etalons are deformed into the shape of a convex lens. Thus, the gap lengths of the fine adjustment etalon 6 and rough adjustment etalon 5 are changed, and hence the central transmission wavelength of the fine adjustment etalon 6 and rough adjustment etalon 5 are shifted from the predetermined wavelength. If the shift of the central transmission wavelength of the rough adjustment etalon 5 is represented by $\Delta\lambda_1$ and the shift of the gap length thereof by Δd_1, the relation between the two is given by the following equation (5):

$$\Delta\lambda_1/\lambda=\Delta d_1/d_1 \tag{5}$$

Further, the free spectral region FSR_1 of the rough adjustment etalon 5 is expressed by the following equation (6):

$$FSR_1=\lambda_2/2nd\cos\theta_1 \tag{6}$$

Thus, the wavelength shift can be expressed by the following equation (7)

$$\Delta\lambda_1=\Delta d_1\,FSR_1/\lambda \tag{7}$$

Similarly, if the wavelength shift of the fine adjustment etalon 6 is represented by $\Delta\lambda_2$, it is expressed by the following equation (8):

$$\Delta\lambda_2=\Delta d_2\,FSR_2/\lambda \tag{8}$$

The variation Δd of the gap length of the etalons is determined by the dimensions of the substrate plates of the etalons, the relevant physical constants, and the output power of the laser beam. Thus, if the plates of the two etalons 5 and 6 are designed identically, the variations Δd_1 and Δd_2 of the gap lengths of the rough adjustment etalon 5 and fine adjustment etalon 6 are made equal to each other. Then, the shift $\Delta\lambda_1$ of the central transmission wavelength of the rough adjustment etalon 5 can be expressed by the following equation (9):

$$\Delta\lambda_1=(FSR_1/FSR_2)\,\Delta\lambda_2 \tag{9}$$

Thus, on the basis of this equation (9), the shift of the central transmission wavelength of the rough adjust-

ment etalon 5 can be inferred from the ratio (FSR_1/FSR_2) of the free spectral regions of the rough adjustment etalon 5 and fine adjustment etalon 6 and the shift $\Delta\lambda_2$ of the central transmission wavelength of the fine adjustment etalon 6. By the way, the oscillation wavelength of the laser beam is, as noted above, determined solely by the central transmission wavelength of the fine adjustment etalon 6. Thus, the central transmission wavelength of the fine adjustment etalon 6 can be determined directly by measuring the oscillation wavelength of the laser beam by means of the first interference fringe detector 9. The wavelength of the laser beam measured by the first interference fringe detector 9 is outputted to the calculation means 26. In response thereto, the calculation means 26 obtains the shift of the oscillation wavelength of the laser beam relative to the predetermined wavelength, which shift corresponds to the shift of the central transmission wavelength of the fine adjustment etalon 6, as noted above. The shift of the central transmission wavelength of the rough adjustment etalon 5 is calculated therefrom in accordance with the above equation (9).

The calculation means 26 outputs to the second etalon control mechanism 27 the shift of the central transmission wavelength of the rough adjustment etalon 5 obtained as above. In response thereto, the second etalon control mechanism 27 tunes the central transmission wavelength of the rough adjustment etalon 5 to the predetermined wavelength by adjusting the gap length d, the sealing pressure, or the angle, of the rough adjustment etalon 5.

Further, when the oscillation of the laser beam is continued, thermal deformations are generated in the etalons as shown in FIG. 5, such that the oscillation wavelength of the laser beam is deviated from the predetermined wavelength as shown in FIG. 9. The shift of the central oscillation wavelength of the etalons occurs toward a predetermined direction. Thus, the control time required for attaining the maximum output power can be shortened by shifting, simultaneously with the start of oscillation, the central transmission wavelengths of the rough adjustment etalon 5 and the fine adjustment etalon 6 toward the direction to which the central transmission wavelengths should be shifted if no control is effected.

Furthermore, with respect to the embodiment, the case where the dimensions of the substrate plates constituting the rough adjustment etalon 5 and the fine adjustment etalon 6 or the values of the relevant physical constants are equal to each other for the two etalons has been described. When these values are different from each other for the two etalons, the variations Δd_1 and Δd_2 of the gap length of the fine adjustment etalon 6 and rough adjustment etalon 5 also take different values. Even under such circumstances, however, the shift of the central transmission wavelength of the rough adjustment etalon 5 can be inferred by modifying the above equation (9) by multiplying it with an appropriate correction factor. Thus, the central transmission wavelength of the rough adjustment etalon 5 can be controlled in a manner similar to the above.

FIG. 10 shows another laser device according to this invention. In the case of this laser device, the shift of the central transmission wavelength of the rough adjustment etalon 5 caused by a factor other than the thermal deformation can also be adjusted. In FIG. 10, a second partially reflective mirror 28 reflects part of the laser beam 7 outputted from the laser resonator 1, and a power monitor mechanism 29 detects the output power of the laser beam by means of the light guided thereto via the second partially reflective mirror 28. The power monitor mechanism 29 consists of a unit for measuring the output power of the laser beam and another unit for recording the thus measured output power of the laser beam. The power monitor mechanism 29 judges whether the output of the laser beam increases or decreases upon control of the rough adjustment etalon 5 in either direction, and then determines, on the basis of the preceding judgment, in which direction and by what amount the rough adjustment etalon 5 is to be controlled. A selection control mechanism 30 controls the need or the priority of the signals from the power monitor mechanism 29 and the calculation means 26.

In the case of the laser device as described above, the wavelength of the laser beam is selected by the rough adjustment etalon 5 and fine adjustment etalon 6, and thus a laser beam narrowed in bandwidth is outputted. Further, after the start of laser beam oscillation, the central transmission wavelength of the rough adjustment etalon 5 and the fine adjustment etalon 6 are controlled. When the laser beam oscillation is stabilized thereafter, the selection control mechanism 30 is switched to the side of the power monitor mechanism 29, and the output power P_0 of the laser beam is measured and recorded by the power monitor mechanism 29. Next, the central transmission wavelength of the rough adjustment etalon 5 is slightly shifted by means of the second etalon control mechanism 27, and the output power P of the laser beam is measured again. The second measurement P of the output power is compared with the previous measurement P_0. When the two measurements are different from each other, the rough adjustment etalon 5 is controlled and adjusted by the second etalon control mechanism 27. The direction of adjustment is determined in accordance with whether $P>P_0$ or $P<P_0$ holds. This control operation is repeated until the output power of the laser beam reaches a stable maximum. As a result, laser beam of stabilized output power is outputted at a predetermined wavelength.

The above control operation is described in further detail. It has been pointed out that the thermal deformations of the rough adjustment etalon 5 and the fine adjustment etalon 6 caused by the heat generated by the laser beam give rise to temporary shifts of the central transmission wavelengths. This, however, is not the sole cause of the shifts of the central transmission wavelength of the etalons. Namely, the gap length of the etalons may be changed permanently by a long use or by a displacement of fixing positions caused, for example, by oscillations. Usually, these permanent shifts of the central transmission wavelength of the etalons do not occur simultaneously nor with equal magnitude for the rough adjustment etalon 5 and the fine adjustment etalon 6. Thus, there appears a separation between the central transmission wavelengths of the rough adjustment etalon 5 and the fine adjustment etalon 6. Under such circumstances, even if the central transmission wavelength of the etalons are controlled in accordance with the equation (9) as described above, the central transmission wavelength of the rough adjustment etalon 5 remains deviated from that of the fine adjustment etalon 6, and hence the output power of the laser beam is reduced.

According to the embodiment of FIG. 10, however, the central transmission wavelength of the rough ad-

justment etalon 5 is controlled, after the start of the oscillation, on the basis of the output of the power monitor mechanism 29 which measures the output power of the laser beam. Thus, the rough adjustment etalon 5 is first controlled by the second etalon control mechanism 27 to maximize the output power of the laser beam, and hence the central transmission wavelength of the rough adjustment etalon 5 is tuned to that of the fine adjustment etalon 6. Thereafter, the rough adjustment etalon 5 is controlled in accordance with the equation (9), with an appropriate correction which takes into consideration the difference in the central transmission wavelengths of the rough adjustment etalon 5 and the fine adjustment etalon 6 at the original non-controlled states. Thus, the embodiment of FIG. 10 is capable of adjusting not only the temporary shifts of central transmission wavelength caused by thermal deformations, but also the permanent shifts caused by other factors, and hence can generate a laser beam which is further stabilized in output power and oscillation wavelength.

Referring next to FIG. 11, still another embodiment according to this invention is described. The laser device of FIG. 1 adjusts the permanent shift of the central transmission wavelength of the laser device by a different method.

In FIG. 11, a light source 31, opposing the rough adjustment etalon 5 via the totally reflective mirror 3, emits light at a stable wavelength which is different from the oscillation wavelength of the laser resonator 1. For example, the light source 31 consists of the helium-neon (He-Ne) laser oscillating at the wavelength of 633 nm. The totally reflective mirror 3 has such a coating that is transparent to the wavelength of the helium-neon (He-Ne) laser. A beam splitter 32, disposed between the light source 31 and the totally reflective mirror 3, divides the light 33 emitted from the light source 31 into reflected and transmitted parts. The direction of the reflected light 33*b* is changed by a mirror 34 toward the rough adjustment etalon 5. The transmitted light 33*a* is transmitted through the totally reflective mirror 3, reflected by the rough adjustment etalon 5, and then is received by a first photosensor 35*a*. The first photosensor 35*a* detects the intensity of the light incident thereon. A second photosensor 35*b* detects the intensity of the light 33*b* which is incident thereon after being reflected by the rough adjustment laser 5. The light source 31 and the mirror 34, etc., are arranged in such a manner that the difference of the outputs of the first photosensor 35*a* and second photosensor 35*b* vanishes when the central transmission wavelength of the rough adjustment etalon 5 is tuned to the predetermined wavelength. A processing device 36 processes the signals outputted from the first photosensor 35*a* and second photosensor 35*b*.

The wavelength of the laser beam is selected by the rough adjustment etalon 5 and fine adjustment etalon 6, and thus a laser beam narrowed in bandwidth is outputted. Further, after the start of laser beam oscillation, the central transmission wavelength of the rough adjustment etalon 5 and fine adjustment etalon 6 are controlled. In addition, in the case of this embodiment, the permanent shift of the central transmission wavelength of the rough adjustment etalon 5 is adjusted during the oscillation cessation periods on the basis of the measurements of the variations of the intensity of the light detected by the first photosensor 35*a* and the second photosensor 35*b*.

The method of controlling the rough adjustment etalon 5 during the laser output cessation periods is described by reference to FIGS. 2, 11 and 12, wherein FIG. 12 shows the relation between the outputs of the first photosensor 35*a* and second photosensor 35*b*. First, the helium-neon (He-Ne) laser light source 31 is activated and the helium-neon (He-Ne) laser light 33 emitted from the light source 31 is divided into the transmitted light 33*a* and reflected light 33*b* by the beam splitter 32. A part of the transmitted light 33*a* transmitted through the totally reflective mirror 3 is reflected by the reflective surfaces 5*b* of the rough adjustment etalon 5, and the intensity of the light reflected by the rough adjustment etalon 5 is detected by the first photosensor 35*a*. On the other hand, the reflected light 33*b* reflected by the beam splitter 32 is directed toward the rough adjustment etalon 5, and is reflected by the reflective surfaces 5*b* of the rough adjustment etalon 5. The intensity of the reflected light 33*b* is detected by the second photosensor 35*b*.

As shown in FIG. 12, the reflection light intensities detected by the first photosensor 35*a* and the second photosensor 35*b* vary with the change of the central transmission wavelength of the rough adjustment etalon 5. Thus, the central transmission wavelength of the rough adjustment etalon 5 can be determined from the measurements of the reflection light intensities. Since the incident angles of the lights 33*a* and 33*b* on the rough adjustment etalon 5 are different from each other, the outputs of the first photosensor 35*a* and the second photosensor 35*b* are shifted from each other, as shown in FIG. 12. The differential output of the first photosensor 35*a* and the second photosensor 35*b* (i.e., the difference between the outputs of the first photosensor 35*a* and the second photosensor 35*b*) is represented by a dot-and-dash curve in FIG. 12.

The outputs of the first photosensor 35*a* and the second photosensor 35*b* are supplied to the processing device 36, and the central transmission wavelength of the rough adjustment etalon 5 is controlled to the predetermined wavelength by adjusting the sealing pressure, gap length d, or the angle with respect to the laser beam, of the rough adjustment etalon 5.

This control of the rough adjustment etalon 5 during the laser output cessation periods can also be performed during the laser oscillation periods. However, since the light from a separate helium-neon (He-Ne) laser light source 31 is utilized for the control, error may arise when the light from the light source 31 suffers variations. Thus, after the start of the oscillation of the laser beam 7 itself, the control of the rough adjustment etalon 5 is preferred to be effected on the basis of the output of the calculation means 26, the switching being effected by the selection control mechanism 30. The rough adjustment etalon 5 can thus be controlled more precisely during the oscillation periods of the laser beam 7.

In summary, in the case of this embodiment, the central transmission wavelength of the rough adjustment etalon 5 caused by factors other than the thermal deformations is adjusted before the start of the oscillation of laser beam 7, and, after the start of oscillation of laser beam 7, the shift of the central transmission wavelength of the rough adjustment etalon 5 due to the thermal deformations is adjusted on the basis of the variations of the output power of the laser beam 7. Thus, a laser beam 7 the wavelength of which is stabilized to the predetermined wavelength can be obtained in a shorter time

after the start of oscillation than in the case of the embodiment of FIG. 10.

Referring next to FIG. 13, still another embodiment according to this invention is described. In FIG. 13(*a*), the fine adjustment etalon 6 is controlled on the basis of the measurements effected by the first interference fringes detector 9, and the oscillation wavelength of the laser beam 7 is thus controlled to the predetermined wavelength. On the other hand, the rough adjustment etalon 5 is controlled by the second etalon control mechanism 27 on the basis of the measurements effected by a reflection light measurement means 38, which measures the reflection light 37 reflected by the rough adjustment etalon 5.

FIG. 14 shows the principle of this control of rough adjustment etalon 5. As shown in FIG. 14, according as the angular displacement or tilt of the rough adjustment etalon 5, which is at 0 (zero) when the rough adjustment etalon 5 and the fine adjustment etalon 6 are tuned to each other, increases, the output power of the laser beam 7 decreases. As the same time, the intensity distribution of the reflection light, detected by the reflection light measurement means 38, changes as shown by contours in the figure. The low light intensity region, indicated by the reference character A in FIG. 14, appears at the center of the beam 37 when the rough adjustment etalon 5 and fine adjustment etalon 6 are tuned to each other. This phenomenon can be explained as follows.

If the laser beam 7 has no lateral extension, all the light must be transmitted through the rough adjustment etalon 5, and the intensity of the reflection light must be limited to a minimum. However, since the laser beam 7 has a substantial lateral extension, part of the laser beam 7 has a certain non-zero angle with respect to the optical axis of the laser resonator 1. When the rough adjustment etalon 5 and the fine adjustment etalon 6 are tuned to each other with respect to the main portion of the laser beam 7 proceeding along the optical axis, the tuning of the rough adjustment etalon 5 become inaccurate near the peripheral regions of the laser beam 7. Thus, the intensity of the reflection light 37 become stronger near the peripheral regions, and a dark portion A appears at the center of reflection light 37. When the tilting angle of the rough adjustment etalon 5 is changed, the tuning is deviated with respect to the main portion of the laser beam 7, and the tuned portion is translated toward the periphery in the lateral cross section of the laser beam. Thus, the dark portion A moves toward the periphery as the angular displacement or tilt of the rough adjustment etalon 5 increases.

The reflection light measurement means 38 detects the variations of this light intensity distribution. The reflection light measurement means 38 may be implemented by an image sensor as shown in FIG. 13(*b*), or by a two-partitioned photosensor as shown in FIG. 13(*c*). The result of the detection is analyzed by the analyzer device 39, and the rough adjustment etalon 5 is controlled by the second etalon control mechanism 27 is response to the output of analyzer device 39, so that the dark portion A would be positioned at the center. This method of control has the advantage that the direction and the magnitude of the necessary control can be determined instantaneously from the position of the dark portion A within the lateral cross section of the laser beam.

Referring next to FIG. 15, a further embodiment is described.

In FIG. 15, the laser resonator 1 comprises a laser medium 2, a totally reflective mirror 3, and a partially reflective mirror 4, wherein the laser medium 2 consists of a krypton fluoride (KrF) excimer laser oscillating at the central wavelength of 248 nm. A light source 31, opposing the rough adjustment etalon 5 via the totally reflective mirror 3, emits light at a stable wavelength which is different from the oscillation wavelength of the laser resonator 1. For example, the light source 31 consists of the helium-neon (He-Ne) laser oscillating at the wavelength of 633 nm. The totally reflective mirror 3 has such a coating that is transparent to the wavelength of the helium-neon (He-Ne) laser. A beam splitter 32, disposed between the light source 31 and the totally reflective mirror 3, divides the light 33 emitted from the light source 31 into reflected and transmitted parts. The direction of the reflected light 33*b* is changed by a mirror 34 toward the rough adjustment etalon 5. The transmitted light 33*a* is transmitted through the totally reflective mirror 3, reflected by the rough adjustment etalon 5, and then is received by a first photosensor 35*a*. The first photosensor 35*a* detects the intensity of the light incident thereon. A second photosensor 35*b* detects the intensity of the reflected light 33*b* which is incident thereon after being reflected by the rough adjustment etalon 5. The light source 31 and the mirror 34, etc., are arranged in such a manner that the difference of the outputs of the first photosensor 35*a* and second photosensor 35*b* vanishes when the central transmission wavelength of the rough adjustment etalon 5 is tuned to the predetermined wavelength. A rough adjustment etalon control mechanism 41 controls the transmission wavelength of the rough adjustment etalon 5 by changing the gap length d, or the angle θ relative to the laser beam, of the rough adjustment etalon 5.

The light bounces back and forth within the laser resonator 1 and thus is amplified. Further, the light is narrowed in the bandwidth by the rough adjustment etalon 5 and the fine adjustment etalon 6. Thus, a substantially monochromatic laser beam 7 can be obtained. Further, for the stabilization of the oscillation wavelength of the laser beam, the etalons are controlled. The method of control of the fine adjustment etalon 6 is the same as described above with respect to the first embodiment. On the other hand, the method of control of the rough adjustment etalon 5 is as follows.

Since the output wavelength of the laser beam depends solely on the transmission wavelength of the fine adjustment etalon 6, some other means must be provided for measuring the transmission wavelength of the rough adjustment etalon 5. Thus, in the case of this embodiment, a laser light from a helium-neon (He-Ne) laser light source 31 having a wavelength different from that of the laser beam 7 is radiated on the rough adjustment etalon 5. The helium-neon (He-Ne) laser light 33 emitted from the light source 31 is divided into the transmitted light 33*a* and reflected light 33*b* by the beam splitter 32. A part of the transmitted light 33*a* is transmitted through the totally reflective mirror 3, which is coated with a layer sufficiently transparent to the wavelength of the helium-neon (He-Ne) laser. The transmitted light 33*a* transmitted through the totally reflective mirror 3 is reflected by the reflective surfaces 5*b* of the rough adjustment etalon 5, and the intensity of the light reflected by the rough adjustment etalon 5 is detected by the first photosensor 35*a*. On the other hand, the reflected light 33*b* reflected by the beam splitter 32 is directed toward the rough adjustment etalon 5,

and is reflected by the reflective surfaces 5*b* of the rough adjustment etalon 5. The intensity of the reflected light 33*b* is detected by the second photosensor 35*b*. The outputs of the first photosensor 35*a* and second photosensor 35*b* are supplied to the rough adjustment etalon control mechanism 41. The first photosensor 35*a* and the second photosensor 35*b* are set in such a manner that the differential output of the first photosensor 35*a* and the second photosensor 35*b* (the difference between the outputs of the first photosensor 35*a* and second photosensor 35*b*) vanishes when the central transmission wavelength of the rough adjustment etalon 5 is tuned to the predetermined wavelength. Thus, in response to the outputs of the first photosensor 35*a* and second photosensor 35*b*, the rough adjustment etalon control mechanism 41 controls the rough adjustment etalon 5 so as to reduce the differential output of the first photosensor 35*a* and the second photosensor 35*b* to zero, by changing the gap length d, or the angle relative to the laser beam, of the rough adjustment etalon 5. Thus, the central transmission wavelength of the rough adjustment etalon 5 is controlled to the predetermined wavelength.

Next, the method of control of the rough adjustment etalon 5 is described in detail by reference to FIG. 16. If the reflectivity, with respect to the wavelength of the helium-neon (He-Ne) laser, of the reflective surfaces 5*b* facing the gap of the rough adjustment etalon 5 is represented by R, the ration B of the light reflected back to the first photosensor 35*a* is expressed by the following equation (10)

$$B=\{4R\sin^2(\delta_2/2)\}/\{(1-R)^2+4R\sin^2(\delta_1/2)\}$$

wherein

$$\delta_1=4\pi\ nd\cos\theta_1/\lambda$$

and

nd represents the optical gap length of the etalon;

λ represents the wavelength of the helium-neon (He-Ne) laser; and

θ_1 represents the incident angle of the light from the helium-neon (He-Ne) laser light source 31.

On the other hand, the central transmission wavelength of the rough adjustment etalon 5 is represented by the equation (1). Thus, the ratio B of the reflection light reflected back to the first photosensor 35*a* depends on the variation of the central transmission wavelength of the rough adjustment etalon 5, and this ratio B is measured by the intensity of the light incident on the first photosensor 35*a*. Thus, on the basis of the measurements of the reflection light intensity on the first photosensor 35*a*, the central transmission wavelength of the rough adjustment etalon 5 can be determined. On the other hand, the ratio B of the light reflected back to the second photosensor 35*b* is expressed by an equation similar to the equation (10), although the incident angle θ_2 is different from that for the first photosensor 35*a*.

FIG. 16 shows the relation between the outputs of the first photosensor 35*a* and the second photosensor 35*b*, which is similar to that shown in FIG. 12. As in the case of the embodiment of FIG. 11, the second partially reflective mirror 28 is disposed such that the relation:

$$\delta_1-\delta_2=\pi/2$$

holds. Further as in the case of the embodiment of FIG. 11, the light source 31 and the mirror 34 are disposed in such a manner that the central transmission wavelength of the rough adjustment etalon 5 agrees with the predetermined wavelength of the excimer laser when the differential output of the first photosensor 35*a* and the second photosensor 35*b*, represented by the dot-and-dash curve in FIG. 16, vanishes. Thus, the rough adjustment etalon control mechanism 41 adjusts the rough adjustment etalon 5 such that the differential output of the first photosensor 35*a* and the second photosensor 35*b* will vanish, and the excimer laser is thereby stabilized to the predetermined wavelength.

This method of controlling the rough adjustment etalon 5 is applicable to the case where the reflectivity R is small, since the outputs of the first photosensor 35*a* and the second photosensor 35*b* can be amplified by respective amplifiers. Further, even when the characteristic of the etalon deteriorates due to a long service and the reflectivity thereof is reduced, the outputs of the first photosensor 35*a* and the second photosensor 35*b* decrease simultaneously. Thus, the position at which the differential output of the first photosensor 35*a* and the second photosensor 35*b* vanishes does not suffer a substantial shift. Thus, the central transmission wavelength of the rough adjustment etalon 5 can be controlled accurately to the predetermined wavelength.

The control of the rough adjustment etalon 5 according to the above method can be performed when the laser beam is not oscillated. Further, components such as the 21 and the imaging element 22 can be dispensed with. Furthermore, since the light from the helium-neon (He-Ne) laser 31 is radiated on the portion of the rough adjustment etalon 5 where the laser beam 7 actually passes, the method is convenient for observing the local thermal deformation of the rough adjustment etalon 5 caused by the excimer laser 7.

It is further noted that the variation of the output of the photosensors increases as the magnitude of the reflectivity R of the reflective surfaces 5*b* of the rough adjustment etalon 5 increases. Thus, the increase of the reflectivity R enhances the measurement precision. Further, the variation of the differential output of the first photosensor 35*a* and the second photosensor 35*b*, caused by the shift of the wavelength, can be increased by adjusting the incident angles θ_1 and θ_2 of the helium-neon (He-Ne) laser light on the rough adjustment etalon 5, thereby further enhancing the precision of the measurement of the transmission wavelength.

Further, the helium-neon (He-Ne) laser light source 31 may be implemented by a helium-neon (He-Ne) laser which is utilized for the adjustment of the laser resonator 1 in the production of the laser device. Thus, the production cost can be reduced.

FIG. 17 shows the essential portion of still another embodiment according to this invention. The difference from the laser device of FIG. 15 is as follows. The first photosensor 35*a* and the second photosensor 35*b* are disposed near to each other. The beam splitter 32 for dividing the light of the light source 31 is not utilized, and instead of the beam splitter 32, a concave lens 42 is disposed between the light source 31 and the totally reflective mirror 3.

The method of operation of the laser device of FIG. 17 is as follows. Due to the diverging angle of the laser beams from the light source 31, the outputs of the first photosensor 35*a* and the second photosensor 35*b*, disposed proximate to each other, are differentiated. The rough adjustment etalon 5 is controlled on the basis of the differential output of the first photosensor 35*a* and

the second photosensor 35*b*, in a manner similar to that described above. FIG. 18 shows the differential output of the first photosensor 35*a* and the second photosensor 35*b*. As in the case of the above embodiment, a zero crossing point of the differential output, represented by the dot-and-dash curve in FIG. 18, may be utilized for controlling the central transmission wavelength of the rough adjustment etalon 5. It is noted that the differential output of the first photosensor 35*a*and the second photosensor 35*b* is increased by extending the diverging angle of the laser beam by means of the concave lens 42. Thus, the measurement precision can be enhanced compared with the case where the concave lens 42 is not utilized.

FIG. 19 shows another modification of the embodiment of FIG. 15. In the case of this embodiment, only one photosensor 35*a* is utilized. The method of operation thereof is as follows. The light 33 from the helium-neon (He-Ne) laser light source 31 is reflected by the reflective surfaces 5*b* of the rough adjustment etalon 5 and then is received by the photosensor 35*a*. The intensity of the reflection light incident on the sensor 35*a* is determined in accordance with the above equation (10). The intensity of the reflection light at the time when the central transmission wavelength of the rough adjustment etalon 5 is tuned to the predetermined wavelength of the laser beam is stored in the rough adjustment etalon control mechanism 41, and the rough adjustment etalon control mechanism 41 controls the central transmission wavelength of the rough adjustment etalon 5 to the predetermined wavelength, by adjusting the gap length d or the angle of the rough adjustment etalon 5 relative to the laser beam, such that the intensity of light detected by the sensor 35*a* becomes equal to the stored value thereof. The control in the case where the gap length d of the rough adjustment etalon 5 is adjusted by the variation of the gas pressure is effected as follows.

FIG. 20 shows the reaction between the gas pressure on the etalon and the intensity of the reflection light. In the case where the wavelength of the excimer laser is adjusted to the predetermined wavelength at the gas pressure of 3 atm on the etalon, the intensity of light P detected at the gas pressure is the level to which it should be maintained. Thus, the central transmission wavelength of the rough adjustment etalon 5 is controlled to the predetermined wavelength by maintaining the intensity of the incident light on the sensor 35*a* to the level P. As a result, an excimer laser stabilized at the predetermined wavelength is outputted.

FIG. 21 shows still another modification of the embodiment of FIG. 15. In the case of this embodiment of FIG. 21, the light 33*b* reflected by the beam splitter 32 disposed between the light source 31 and the totally reflective mirror 3 is received directly by the second photosensor 35*b*. The light 33*a* transmitted through the beam splitter 32 is reflected by the rough adjustment etalon 5 and then is received by the first photosensor 35*a*. The output of the second photosensor 35*b* serves as a reference level for the output of the first photosensor 35*a*. Thus, even when the output power of the helium-neon (He-Ne) laser light source 31 varies due to the variations of the source voltage thereof and the intensity of the light incident on the first photosensor 35*a* is thereby changed, the output of the first photosensor 35*a* is normalized with reference to the output of the second photosensor 35*b*. The rough adjustment etalon 5 is controlled by the rough adjustment etalon control mechanism 41 on the basis of this normalized output of the first photosensor 35*a*. Thus, the control of the rough adjustment etalon 5 is not affected adversely by the variation of the output power of the light source 31. Thus, the laser device of FIG. 21 is capable of outputting a laser beam further stabilized in the oscillation wavelength compared with the case of the laser device of FIG. 19.

FIG. 22 shows still another embodiment according to this invention. The embodiment of FIG. 22 is similar to that of FIG. 19, except that a third photosensor 35*c* is provided which detects the intensity of light reflected by the reflective surfaces 5*b* of the fine adjustment etalon 6. In the case of this laser device, the control of the fine adjustment etalon 6 can also be effected by means of the light of the helium-neon (He-Ne) laser light source 31 in a manner similar to that for the rough adjustment etalon 5. The organization of the laser device can thus be simplified since the integrator 10 or the etalon 11 for forming the interference fringes can be disposed with.

In the case of the above embodiments, the light source 31 opposes the rough adjustment etalon 5 via the totally reflective mirror 3, and the light emitted from the light source 31 is radiated on the rough adjustment etalon 5 via the totally reflective mirror 3. However, the light source 31 may be disposed at a position radially displaced from the optical axis of the laser resonator 1, such that the light emitted from the light source 31 may be radiated directly on the rough adjustment etalon 5 from a tilted direction. In such case, it is not necessary that the wavelength of the light source 31 is differentiated from that of the laser beam 7.

What is claimed is:

1. A laser device comprising:

a laser resonator including a first and a second etalon having distinct transmission bandwidths, wherein a transmission bandwidth of the first etalon is narrower than a transmission bandwidth of the second etalon;

measurement means for measuring an oscillation wavelength of a laser beam outputted from said laser resonator;

first control means, coupled to an output of said measurement means, for controlling the transmission wavelength of the first etalon such that the oscillation wavelength of the laser beam detected by the measurement means is adjusted to a predetermined wavelength;

calculation means, coupled to an output of said measurement means, for calculating a shift of the transmission wavelength of the second etalon in response to a measurement of the oscillation wavelength of the laser beam effected by the measurement means; and

second control means, coupled to an output of the calculation means, for controlling the transmission wavelength of the second etalon to the predetermined wavelength in response to the output of the calculation means.

2. A laser device as claimed in claim 1, further comprising:

a power monitoring means for measuring the output power of the laser beam outputted from the laser resonator; and

selection control means for selectively supplying outputs of the calculation means and the power monitoring means to said second control means, said second control means controlling the second etalon in response to the selected output of the

calculation means and the power monitoring means.

3. A laser device comprising:

a laser resonator including a first and a second etalon having distinct transmission bandwidths, wherein a transmission bandwidth of the first etalon is narrower than a transmission bandwidth of the second etalon;

a light source emitting light on at least one of said etalons;

photosensor means for detecting an intensity of light emitted from said light source and reflected by said one of the etalons; and

control means, coupled to an output of said photosensor means, for controlling the transmission wavelength of said one of the etalons to a predetermined wavelength in response to the intensity of light detected by said photosensor means.

4. A laser device as claimed in claim 3, wherein said light source emits light at a wavelength different from an oscillation wavelength of a laser beam outputted from the laser resonator, said light source emitting light to said one of the etalons along an optical axis of said laser resonator via a totally reflective mirror of said laser resonator.

5. A laser device as claimed in claim 4, wherein said one of the etalons is said second etalon.

6. A laser device as claimed in claim 5, further comprising: dividing means for dividing the light emitted from the light source into two parts, and wherein said photosensor means comprises a first and a second photosensor for receiving the two divided parts of the light reflected by said second etalon, wherein a difference between outputs of said first and second photosensor vanishes when the transmission wavelength of said second etalon is adjusted to the predetermined wavelength, said control means controlling said second etalon so as to reduce the difference of the outputs of the first and second photosensor to zero.

7. A laser device as claimed in claim 6, wherein said dividing means comprises a beam splitter disposed between the light source and the totally reflective mirror of the laser resonator.

8. A laser device as claimed in claim 5, further comprising: diverging means for diverging the light emitted from the light source into two parts, and wherein said photosensor means comprises a first and a second photosensor for receiving the two diverged parts of the light reflected by said second etalon, wherein a difference between outputs of said first and second photosensor vanishes when the transmission wavelength of said second etalon is adjusted to the predetermined wavelength, said control means controlling said second etalon so as to reduce the difference of the outputs of the first and the second photosensor to zero.

9. A laser device as claimed in claim 8, wherein said diverging means comprises a concave lens disposed between the light source and the totally reflective mirror of the laser resonator.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,130,998

DATED : July 14, 1992

INVENTOR(S) : Hitoshi Wakata et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page [57], line 2 of the abstract, after "stabilization." insert --The rough adjustment etalon is controlled on the basis of the calculation that is effected by calculation means based on the measurement of the output wavelength of the laser beam.--

Col. 1, line 21 "Kohai" should be --Kokai--.

Col. 2, line 7 "form" should be --formed--.

Col. 2, line 32 "wavelength" should be --wavelengths--.

Col. 3, line 25 "turned" should be --tuned--.

Col. 3, line 26 "λ_1" should be --λ_0--.

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. 5,130,998
DATED July 14, 1992
INVENTOR(S) : Hitoshi Wakata et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Col. 4, line 35 "angel" should be --angle--.

Col. 13, line 21 "As" should be --At--.

Col. 13, line 53 "variations" should be --variation--.

Col. 15, line 34 "wherein" should be --where--.

Col. 17, line 38 "reaction" should be --relation--.

Signed and Sealed this

Thirtieth Day of November, 1993

Attest:

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks

United States Patent [19]

Ohshima et al.

[11] **Patent Number: 4,998,256**

[45] **Date of Patent: Mar. 5, 1991**

[54] **SEMICONDUCTOR LASER APPARATUS**

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[73] Assignee: **Kabushiki Kaisha Toshiba**, Kawasaki, Japan

[21] Appl. No.: **501,045**

[22] Filed: **Mar. 29, 1990**

[30] **Foreign Application Priority Data**

Mar. 30, 1989	[JP]	Japan	1-76517
May 25, 1989	[JP]	Japan	1-131857
Jul. 13, 1989	[JP]	Japan	1-180942
Nov. 17, 1989	[JP]	Japan	1-297729
Nov. 20, 1989	[JP]	Japan	1-299687
Nov. 21, 1989	[JP]	Japan	1-300912
Dec. 5, 1989	[JP]	Japan	1-314197

[51] **Int. Cl.**[5] **H01S 3/13**

[52] **U.S. Cl.** **372/32**; 372/92; 372/38; 372/34; 372/43

[58] **Field of Search** 372/32, 29, 87, 38, 372/27, 34, 43

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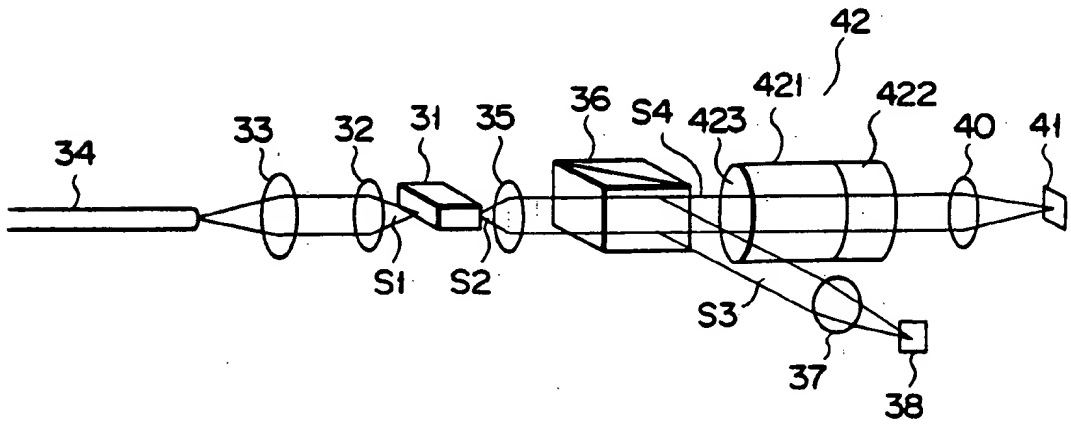
Primary Examiner—Léon Scott, Jr.

Attorney, Agent, or Firm—Oblon, Spivak, McClelland, Maier & Neustadt

[57] **ABSTRACT**

In a semiconductor laser apparatus of the invention, a laser beam emitted from a semiconductor laser is collimated by an optical leans, and is subsequently split by a beam splitter in two directions. One split laser beam component is focused on a first photodetector through an optical lens. The other laser beam component is incident on a Fabry-Perot resonator, and is changed in intensity thereby. The laser beam component is then focused on a photodetector through an optical lens. The Fabry-Perot resonator is integrally designed such that dielectric multilayer films are respectively deposited on both the end faces of a crystalized quartz bulk, which is shaped into a columnar shape extending in the C-axis direction, so as to form a pair of reflect filters. Since the bulk is made of crystalized quartz it is not easily influenced by changes in temperature.

30 Claims, 11 Drawing Sheets



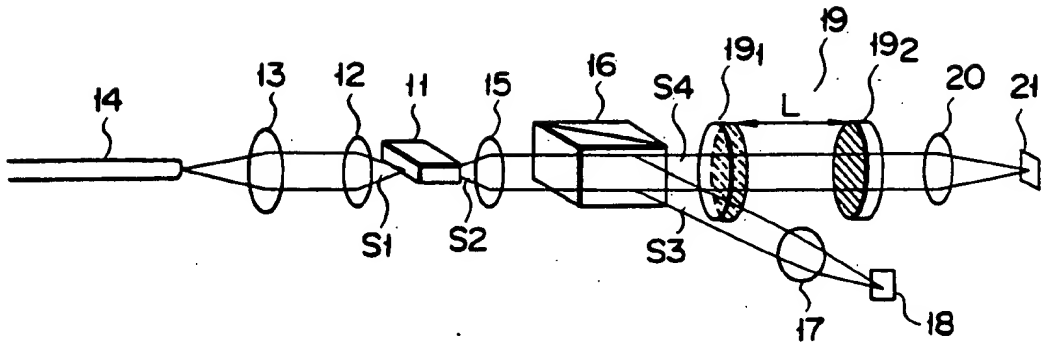


FIG. 1 (PRIOR ART)

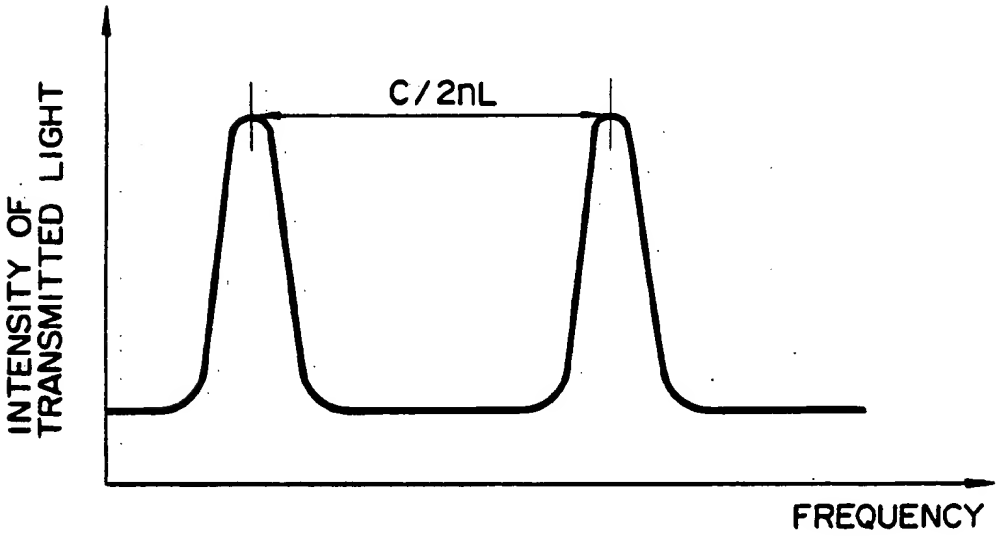


FIG. 2 (PRIOR ART)

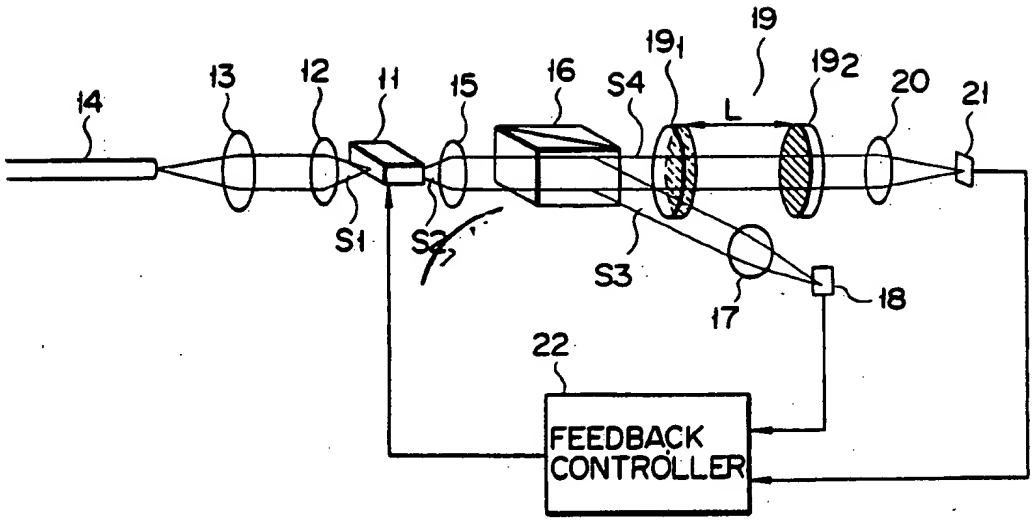


FIG. 3 (PRIOR ART)

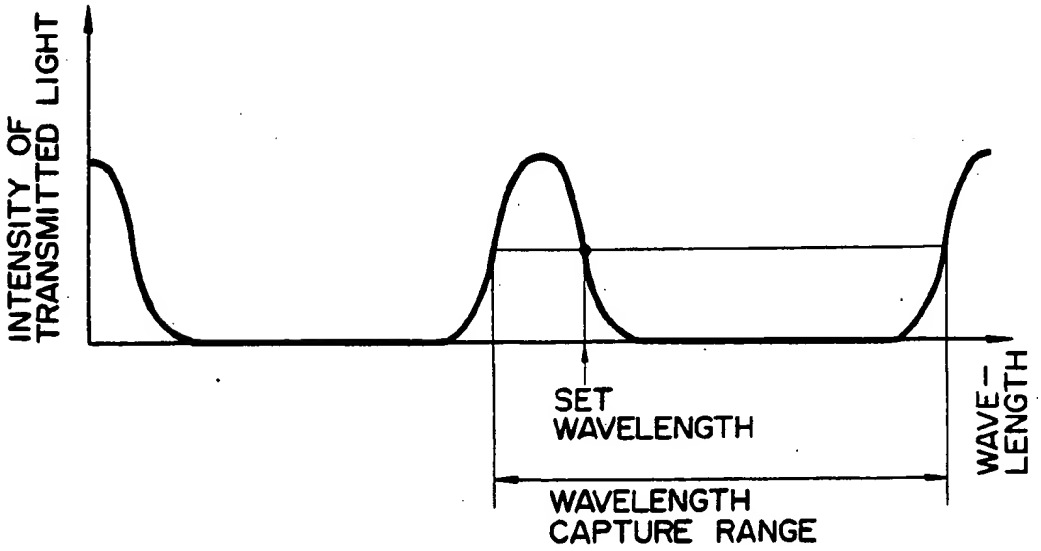
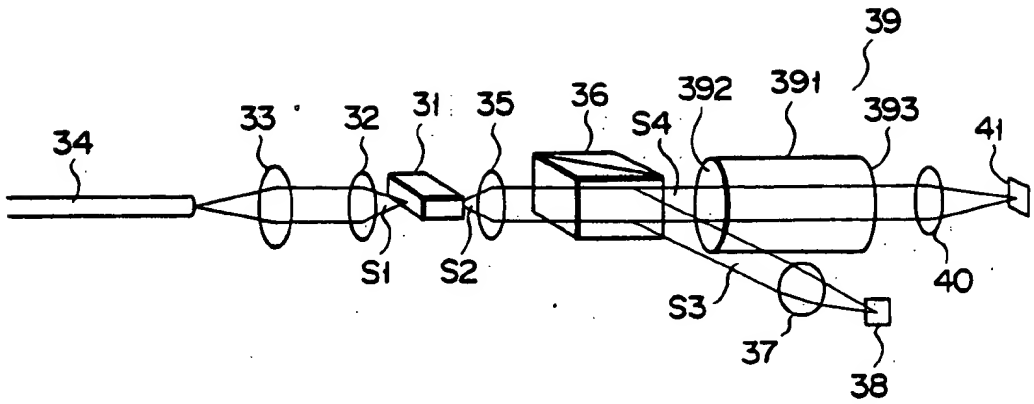


FIG. 4 (PRIOR ART)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34
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S4
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393
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S1
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S3
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FIG. 5

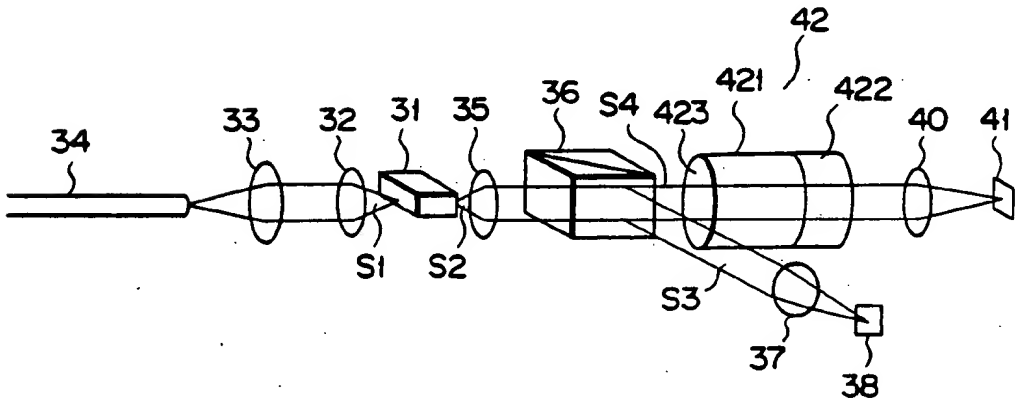
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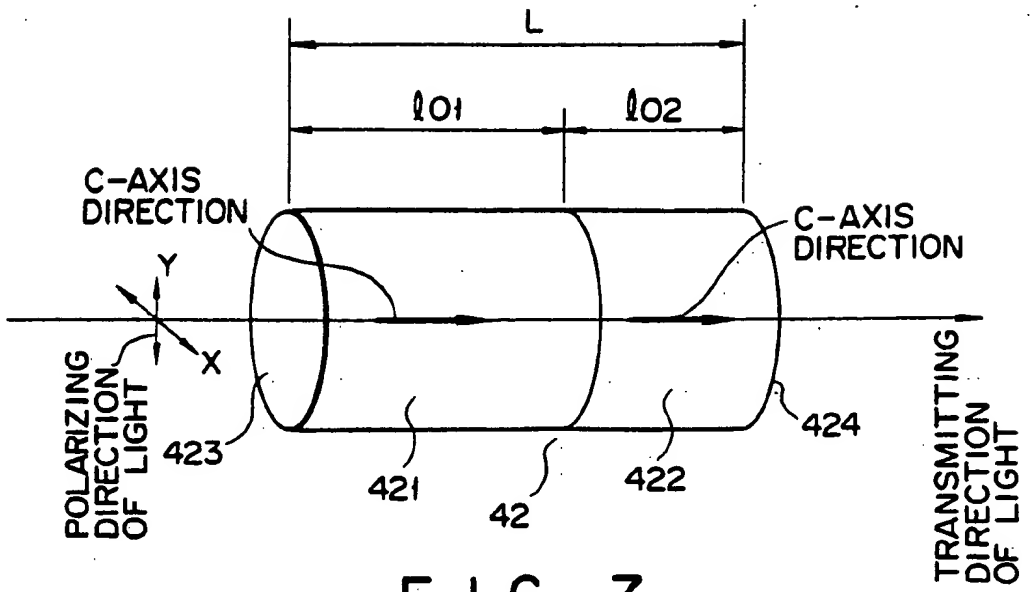
FIG. 6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ℓ01
ℓ02
C-AXIS DIRECTION
C-AXIS DIRECTION
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X
POLARIZING DIRECTION OF LIGHT
TRANSMITTING DIRECTION OF LIGHT
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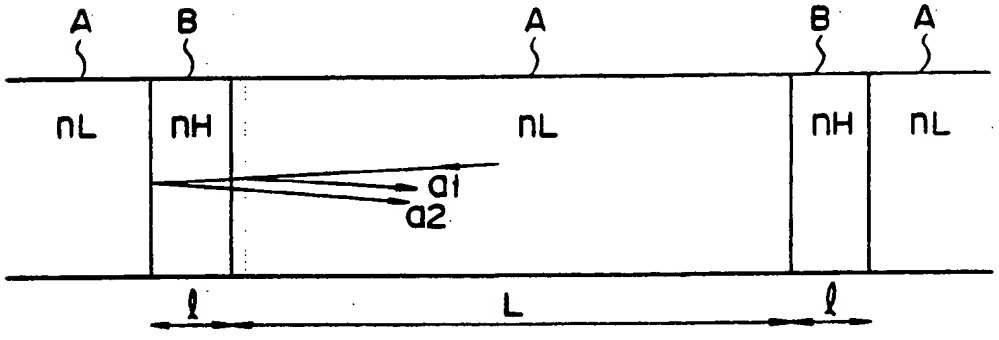
FIG. 7


A
B
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B
A
nL
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nH
nL
a1
a2
ℓ
L
ℓ

FIG. 8

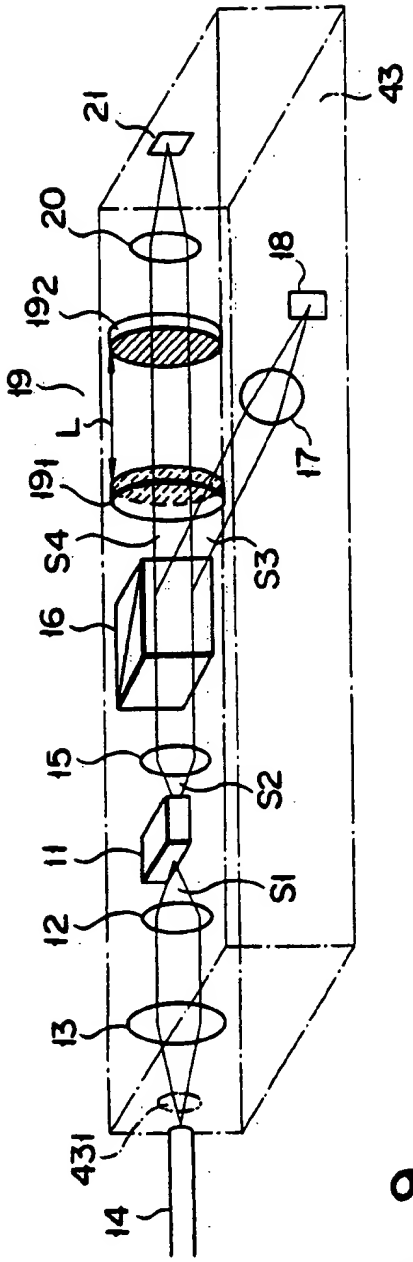
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FIG. 9

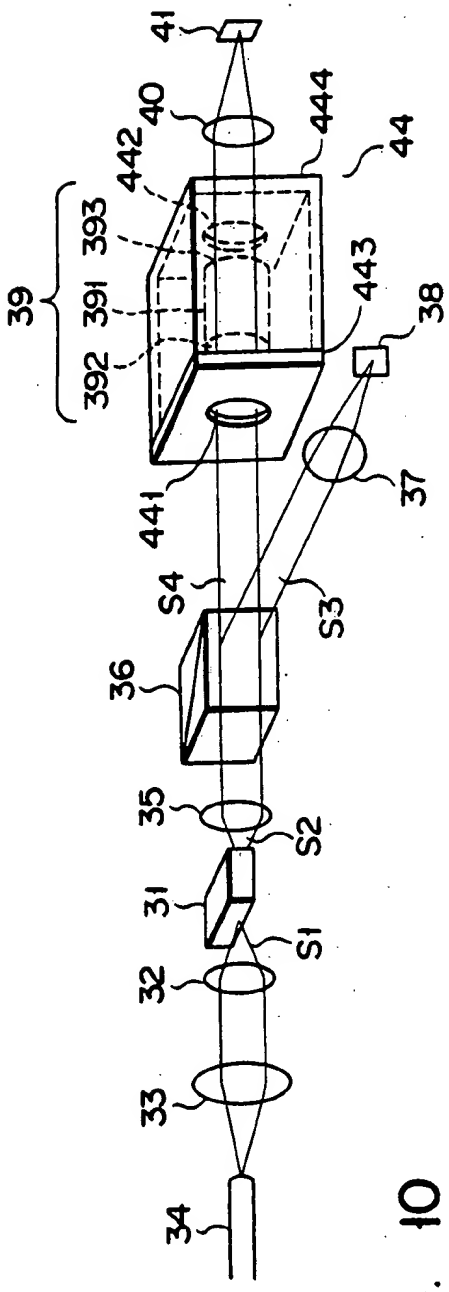
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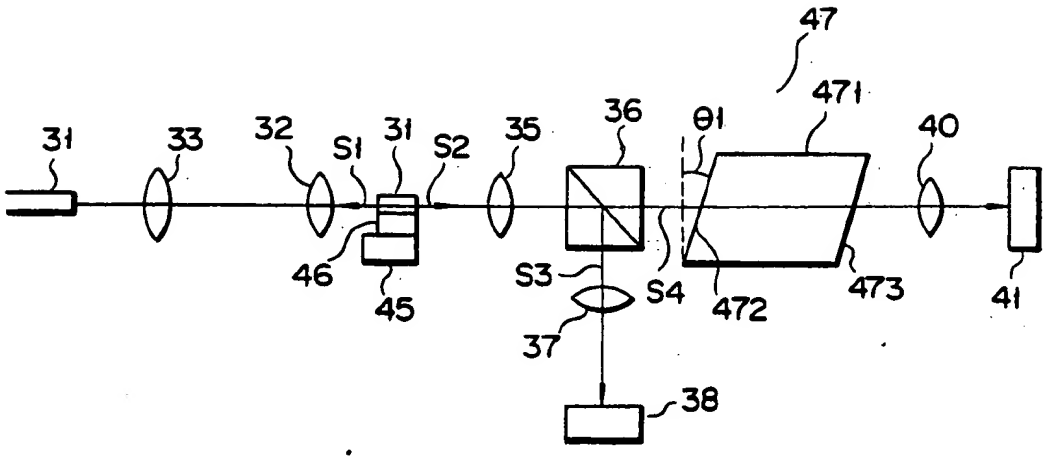
FIG. 10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S3
S4
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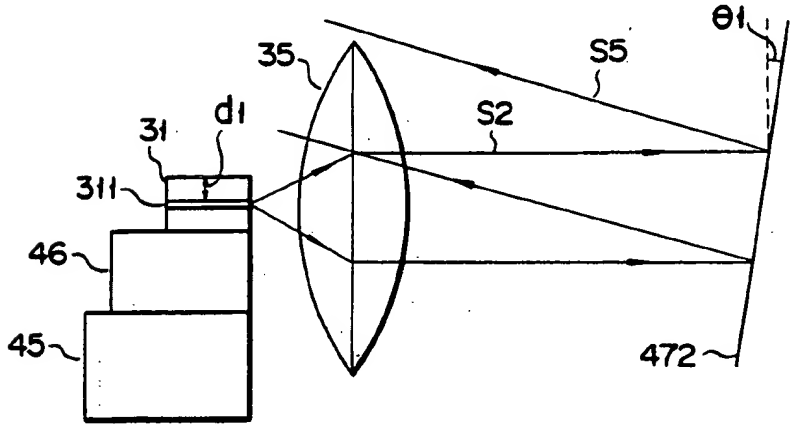
38

FIG. 11


θ1
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S5
S2
31
d1
311
46
45
472

FIG. 12

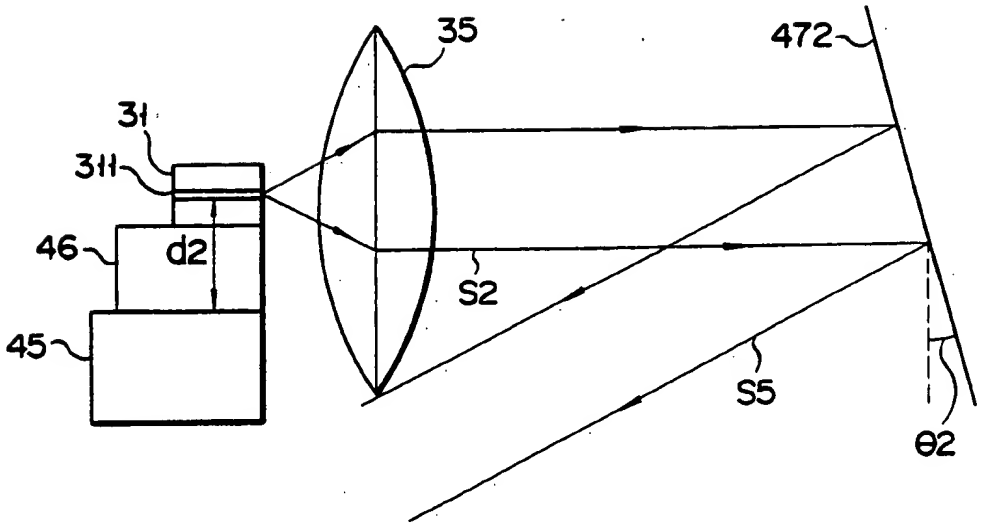

FIG. 13

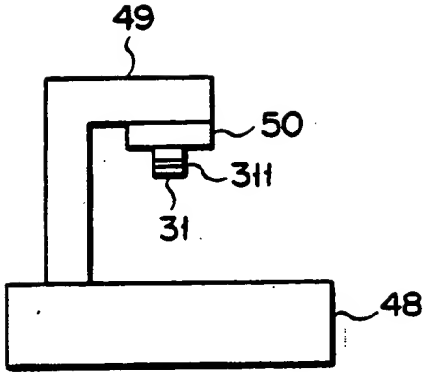

FIG. 14

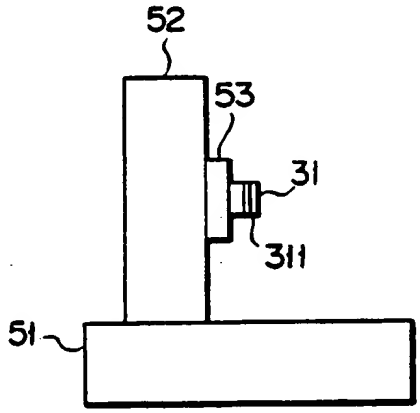

FIG. 15

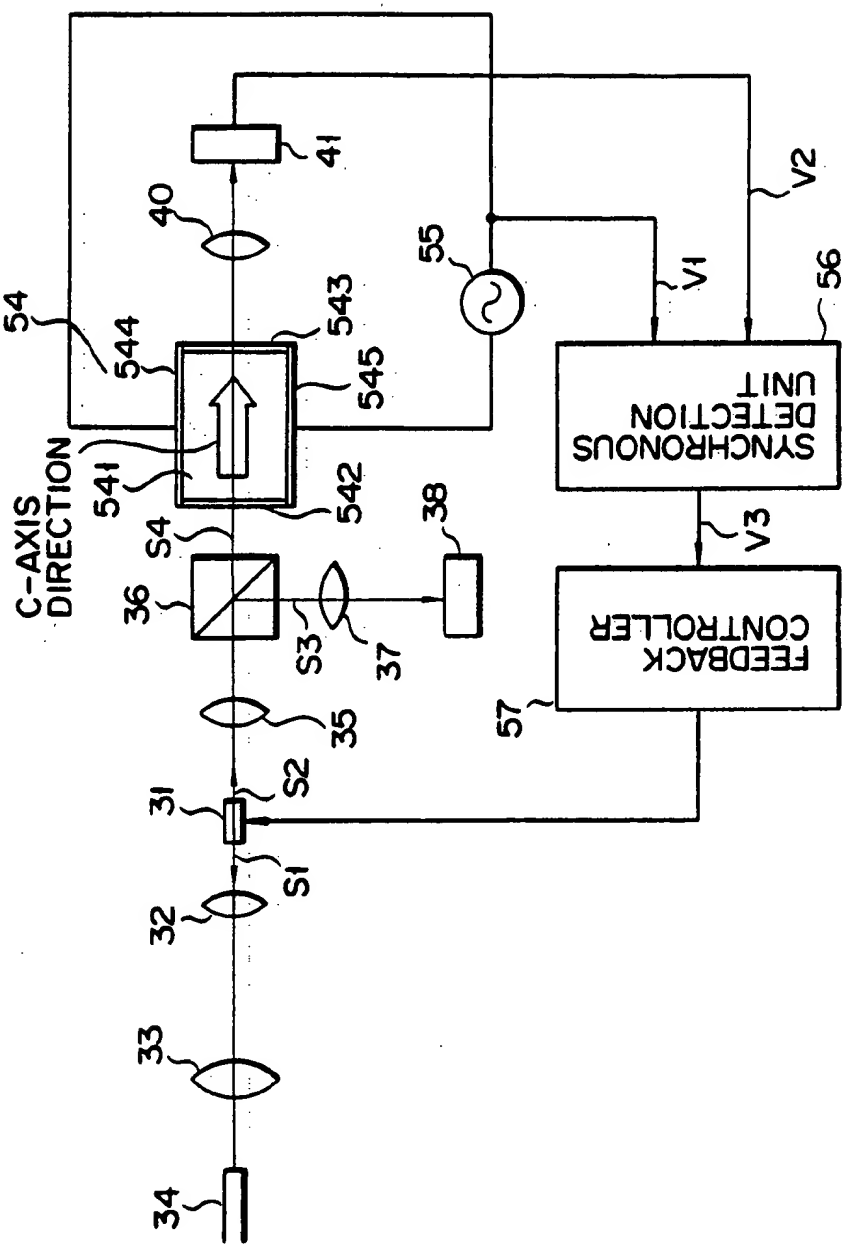
41
40
55
V2
V1
56
54
544
543
545
541
542
C-AXIS DIRECTION
SYNCHRONOUS DETECTION UNIT
S4
38
V3
36
S3
37
FEEDBACK CONTROLLER
57
35
S2
31
S1
32
33
34

FIG. 16

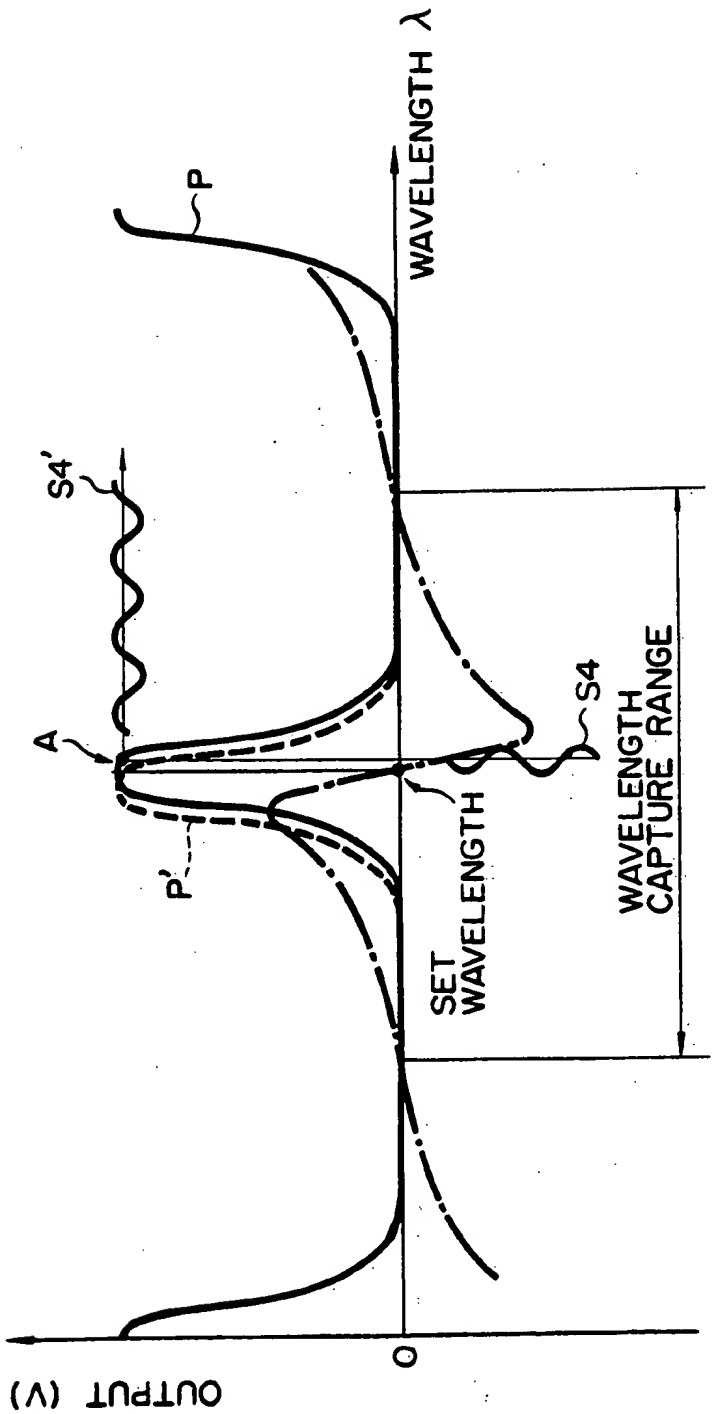
WAVELENGTH λ
P
S4'
A
P'
S4
SET WAVELENGTH
WAVELENGTH CAPTURE RANGE
O
OUTPUT (V)

FIG. 17

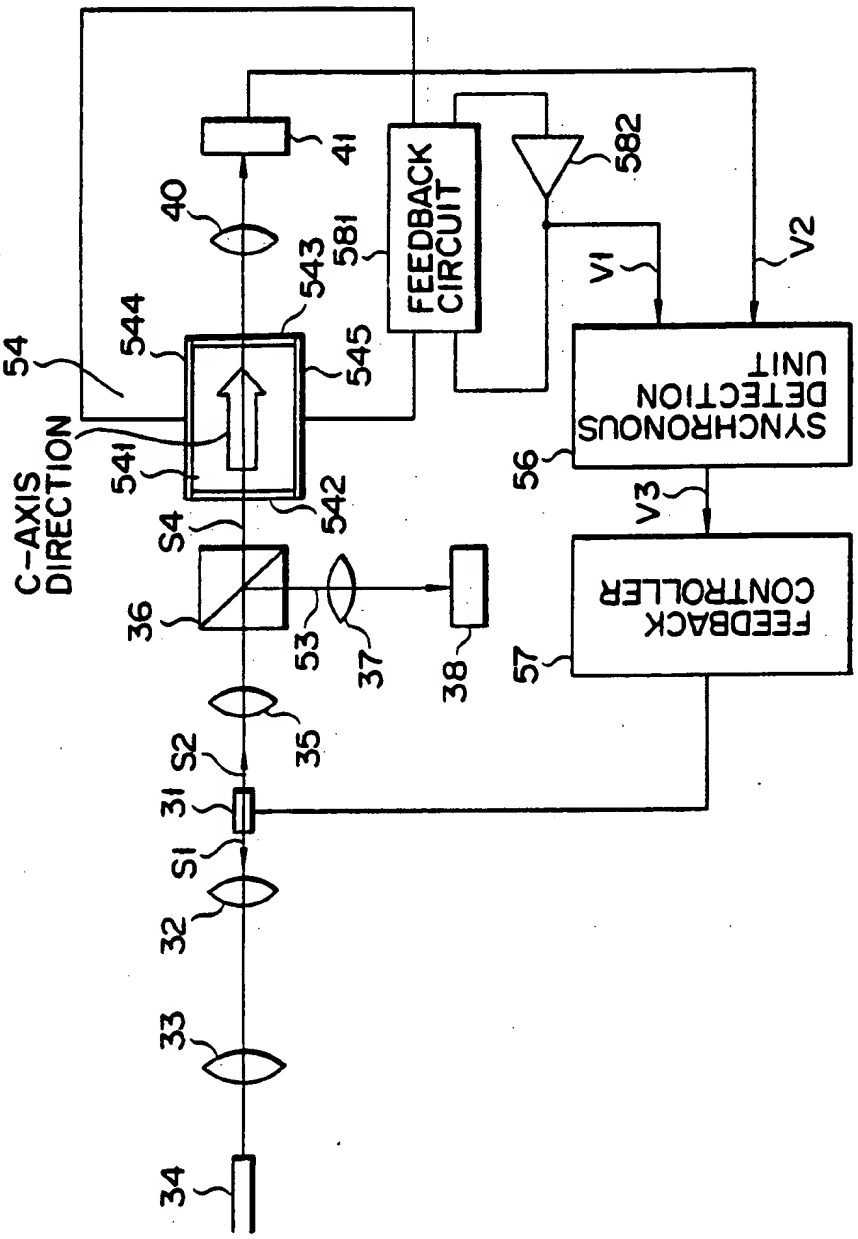
41
582
40
581
FEEDBACK CIRCUIT
543
V1
V2
544
54
545
SYNCHRONOUS DETECTION UNIT
C-AXIS DIRECTION
541
542
56
V3
S4
36
53
37
38
FEEDBACK CONTROLLER
57
35
S2
31
S1
32
33
34

FIG. 18

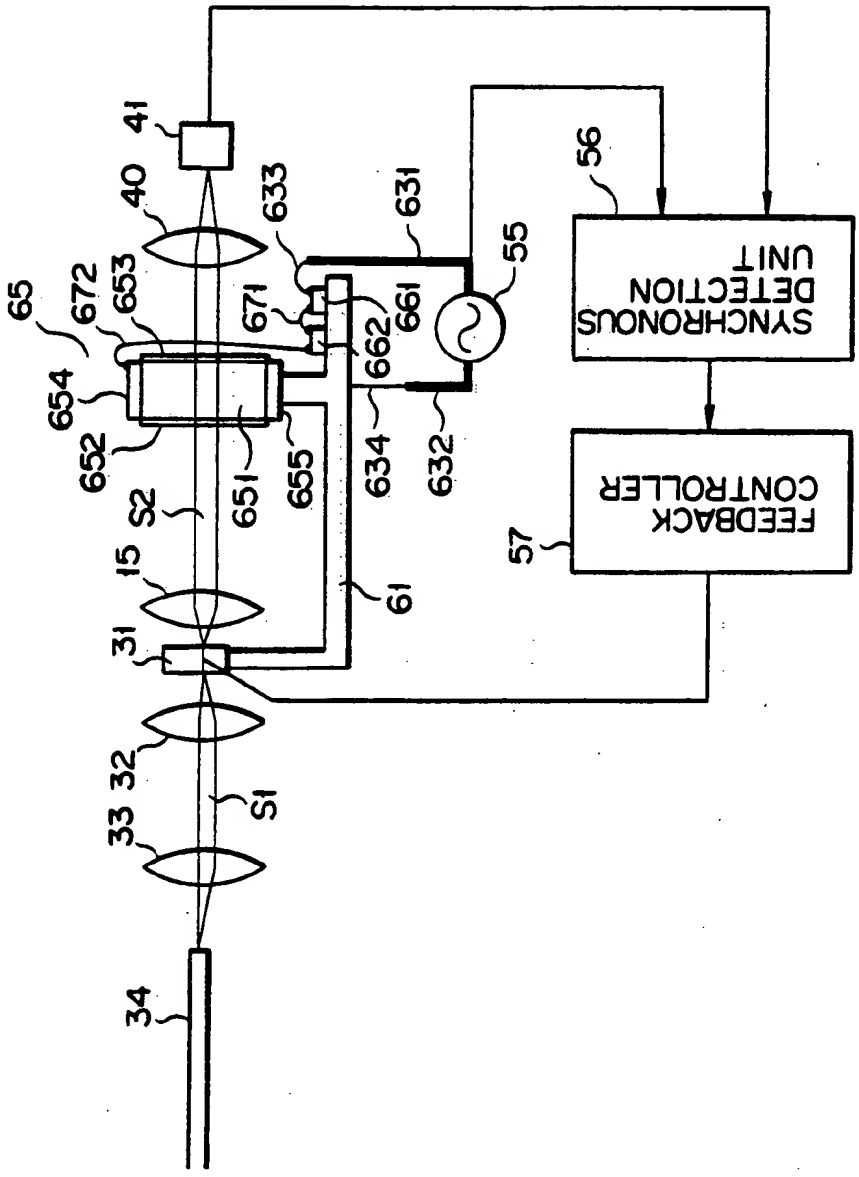
41
40
633
631
56
55
65
672
653
671
661
662
654
652
655
634
632
651
S2
15
61
57
31
32
S1
33
34
SYNCHRONOUS DETECTION UNIT
FEEDBACK CONTROLLER

FIG. 19

SEMICONDUCTOR LASER APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a semiconductor laser module and a laser wavelength control apparatus used for optical communication.

2. Description of the Related Art

FIG. 1 shows a conventional semiconductor laser module which can be used for optical communication.

Referring to FIG. 1, reference numeral 11 denotes a semiconductor laser. The oscillation wavelength (oscillation frequency) of the semiconductor laser 11 can be controlled by changing its injection current or temperature. Light S_1 emitted from the left side of the semiconductor laser 11 in FIG. 1 is focused on an optical fiber 14 for optical transmission through optical lenses 12 and 13. Light S_2 emitted from the right side of the semiconductor laser 11 in FIG. 1 is collimated by an optical lens 15 and is split by a beam splitter 16 in two directions. One split light component S_3 is focused on a first photodetector (e.g., a photodiode) 18 through a optical lens 17. The other light component S_4 undergoes a change in intensity through a Fabry-Perot resonator 19 and is focused on a second photodetector (e.g., photodiode) 21 through an optical lens 20.

The Fabry-Perot resonator 19 is designed such that a pair of reflecting mirrors 191 and 192 each consisting of a dielectric multilayer film are set parallel and oppose each other at a distance L. The Fabry-Perot resonator 19 has a characteristic that a light intensity is repeatedly changed at a period of a free spectral interval C/2nL (C: light velocity; n: refractive index in the Fabry-Perot resonator) with respect to the frequency of incident light, as shown in FIG. 2. For this reason, light which is incident on the Fabry-Perot resonator 19 undergoes a change in intensity in accordance with its frequency, and a detection output from the second photodetector 21 undergoes a change in level due to the change in intensity. Therefore, the oscillation wavelength of the semiconductor laser 11 can be obtained by measuring a ratio of an output from the first photodetector 18, which receives light free from an intensity change, to an output from the second photodetector 21, which receives light which is changed in intensity.

In the conventional apparatus, therefore, as basically shown in FIG. 3, both outputs from the first and second photodetectors 18 and 21 are input to a feedback control unit 22, and an oscillation wavelength is obtained by the control unit 22 on the basis of the level difference between the outputs. The temperature or injection current of the semiconductor laser 11 is changed in accordance with the obtained oscillation wavelength, thereby controlling the oscillation wavelength of the semiconductor laser 11 to be a desired oscillation wavelength. FIG. 4 shows a relationship between the oscillation wavelength of the semiconductor laser 11 and a detection level difference from the feedback control unit 22, and also shows the wavelength capture range of the control unit 22.

The conventional Fabry-Perot resonator 19 used in the above-described semiconductor laser module must be designed under the following conditions and limitations. In the first place, the two reflecting mirrors 191 and 192 must be arranged with a parallelism on the order of seconds. In the second place, the two reflecting mirrors 191 and 192 must be arranged at the interval L on the order of submicrons. In the third place, the ambient temperatures of the two reflecting mirrors 191 and 192 must be controlled with a precision of 0.1° C. or less because the two reflecting mirrors 191 and 192 and their holder (not shown) expand or contract depending on changes in temperature and humidity so as to change the distance L. In the last place, the positions of the two reflecting mirrors 191 and 192 tend to shift from each other due to an external impact. Because of these limitations, the Fabry-Perot resonator 19 is difficult to manufacture. In addition, the Fabry-Perot resonator 19 tends to exhibit variations in characteristics and is susceptible to variation due to external factors. Therefore, stable control of the wavelength of the semiconductor laser is difficult.

In the above-described means for controlling the wavelength of a semiconductor laser, a set wavelength is not located at the center of the wavelength capture range, as shown in FIG. 4. Since the wavelength capture range cannot be effectively used for stable feedback control, such a means is difficult to operate. Especially, if the fineness of the Fabry-Perot resonator 19 is increased to improve its sensitivity, this tendency becomes more conspicuous. Therefore, the sensitivity is difficult to improve. In addition, since control by this means is performed in a DC manner, its operation is susceptible to drifts. That is, the set wavelength precision is affected not only by changes in sensitivity of the photodetectors 18 and 21, changes in sensitivity of an amplifier, arranged in the feedback control unit 22, for amplifying an input signal, and a O-point drift but also by changes in light amount due to dust and the like in an optical path. For this reason, it is very difficult to stabilize a set wavelength over a long period of time.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a semiconductor laser apparatus which allows stable and easy control of the oscillation wavelength of a semiconductor laser, is not easily influenced by temperature and humidity as external factors, and is resistant to changes in quality over years.

A semiconductor laser apparatus comprises a semiconductor laser for emitting a laser beam, a Fabry-Perot resonator including a crystallized quartz bulk having two flat surfaces which are perpendicular to a C-axis direction and parallel and opposite to each other, the Fabry-Perot resonator being provided with dielectric multilayer films respectively deposited on the flat surfaces so as to form reflect filters, and the crystallized quartz bulk being arranged on an optical axis of one of laser beams emitted from the semiconductor laser in such a manner that the C-axis direction is parallel to the optical axis of said semiconductor, thereby detecting a wavelength of incident light; and a photodetector for receiving and photoelectrically converting light which is transmitted through the Fabry-Perot resonator.

A semiconductor laser apparatus comprises a semiconductor laser for emitting a laser beam, a Fabry-Perot resonator which is designed such that two types bulks having different temperature coefficients are bonded to each other to be formed into a bulk assembly, dielectric multilayer films are respectively deposited on two flat surfaces of said bulk assembly, which are formed to be parallel and opposite to each other through bonding surfaces of said bulks, so as to form reflect filters, said bulk assembly being arranged on an optical axis of one

of laser beams emitted from said semiconductor laser in such a manner that the flat surfaces are perpendicular to the optical axis of said semiconductor, thereby detecting a wavelength of incident light; and a photodetector for receiving and photoelectrically converting light which is transmitted through said Fabry-Perot resonator.

Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate presently preferred embodiments of the invention, and together with the general description given above and the detailed description of the preferred embodiments given below, serve to explain the principles of the invention.

FIG. 1 is a view showing an arrangement of a conventional semiconductor laser module;

FIG. 2 is a graph showing the light intensity characteristics of a Fabry-Perot resonator in FIG. 1 with respect to the frequency of incident light;

FIG. 3 is a view showing an arrangement of a laser oscillation wavelength control apparatus of the conventional semiconductor laser module;

FIG. 4 is a graph showing a relationship between the oscillation wavelength of a semiconductor laser controlled by the control apparatus in FIG. 3 and a detection level difference obtained by a feedback control unit, and showing the wavelength capture range of the feedback control unit;

FIG. 5 is a view showing an arrangement of the first embodiment of a semiconductor laser module according to the present invention;

FIG. 6 is a view showing an arrangement of the second embodiment of a semiconductor laser module according to the present invention;

FIG. 7 is an enlarged view of a Fabry-Perot resonator in FIG. 6;

FIG. 8 is a view, showing an arrangement of a Fabry-Perot resonator, for explaining the third embodiment of a semiconductor laser module according to the present invention;

FIG. 9 is a view showing an arrangement of the fourth embodiment of a semiconductor laser module according to the present invention;

FIG. 10 is a view showing an arrangement of the fifth embodiment of a semiconductor laser module according to the present invention;

FIG. 11 is a view showing an arrangement of the sixth embodiment of a semiconductor laser module according to the present invention;

FIGS. 12 and 13 are enlarged views of part of the arrangement of the module in FIG. 11;

FIGS. 14 and 15 are views respectively showing modifications of the sixth embodiment;

FIG. 16 is a view showing an arrangement of a semiconductor laser module and the first embodiment of its laser wavelength control apparatus according to the present invention;

FIG. 17 is a graph, showing the wavelength-output characteristics of each component, for explaining an operation;

FIG. 18 is a view showing an arrangement of the second embodiment of a laser wavelength control apparatus according to the present invention, which is obtained by improving the laser wavelength control apparatus in FIG. 16; and

FIG. 19 is a view showing an arrangement of a semiconductor laser module and the third embodiment of its laser wavelength control apparatus according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 5 shows the first embodiment of a semiconductor laser module according to the present invention. Referring to FIG. 5, reference numeral 31 denotes a semiconductor laser. By changing the injection current or temperature of the semiconductor laser 31, wavelength control in a 1.55-μm wavelength band can be performed. Light S_1 emitted from the left side of the semiconductor laser 31 in FIG. 5 is focused on an optical fiber 34 for optical transmission through optical lenses 32 and 33. Light S_2 emitted from the right side of the semiconductor laser 31 in FIG. 5 is collimated by an optical lens 35 and is split by a beam splitter 36 in two directions. One split light component S_3 is focused on a first photo-detector (e.g., a photodiode) 38 through an optical lens 37. A detection output from the first photodetector 38 is used as a power monitor output. The other split light component S_4 is transmitted through a Fabry-Perot resonator 39 consisting of a crystallized quartz etalon whose C axis is matched with an optical axis of the semiconductor laser 31, and is focused on a second photodetector (e.g., a photodiode) 41 through an optical lens 40.

The Fabry-Perot resonator 39 is designed such that reflect filters 392 and 393 are respectively formed by depositing dielectric multilayer films on both the end faces (top and bottom surfaces) of a bulk 391 which is shaped to extend in the C-axis direction in the form of a column. The parallelism of the surfaces 392 and 393 and a distance L therebetween depend on only the shaping precision of the bulk 391. The bulk 391 can be shaped on the order of seconds in terms of angles and on the order of submicrons in terms of lengths. Any consideration need not be given to a positional shift of the two reflect filters 392 and 393 due to an external impact. In addition, since the reflect filters 392 and 393 are formed on the solid body of the crystallized quartz bulk 391, they are not easily influenced by temperatures.

An optical length L between the two reflect filters 392 and 393 as a function of temperature can be represented by the following equation:

$$L=\{n_0+(dn/dT)\cdot T\}\cdot L_0\cdot(1+\alpha T)=n_0\cdot L_0[1+T\cdot\{\alpha+(1/n_0)\cdot(dn/dT)\}] \quad (1)$$

where n_0 is the refractive index of the crystallized quartz at T=0, dn/dT is an amount of change in refractive index with respect to the temperature, T is the temperature, L_0 is the physical length of the etalon at T=0, and α is a linear expansion coefficient. According to equation (1), the influence of changes in temperature on the optical length L is reduced as the following value is decreased:

$\alpha+(1/n_0)\cdot(dn/dT)$

In this case,

$$\alpha+(1/n_0)\cdot(dn/dT)=\gamma \quad (2)$$

The value γ of fused silica which is often used for an etalon is about 7×10^{-6}/deg. In contrast to this, the crystallized quartz exhibits a very small value γ about 3×10^{-6}/deg, when light is incident in the C-axis direction. Therefore, by using the crystallized quarty bulk **391**, a wavelength detecting precision of 0.1 Å or less can be ensured at about 1° C.

As described above, a Fabry-Perot resonator consisting of a crystallized quartz etalon uses a Z-cut crystallized quartz The temperature coefficient $\gamma(\gamma=\alpha+(1/n)\cdot(dn/dT)$, where α: a linear expansion coefficient; n: a refractive index; dn/dT: an amount of change in refractive index with respect to a temperature change) of the Z-cut crystallized quartz is about 3×10^{-6}/deg. Therefore, even the Fabry-Perot resonator using the Z-cut crystallized quartz having a relatively small temperature coefficient cannot satisfy the demand for temperature control with a precision of 0.1° C. or less.

FIG. **6** shows a semiconductor laser module according to the second embodiment of the present invention, which is designed to solve the above-described problem. The same reference numerals in FIG. **6** denote the same parts as in FIG. **5**, and a description thereof will be omitted.

The semiconductor laser module shown in FIG. **6** is different from that shown in FIG. **5** in the structure of a Fabry-Perot resonator **42**. This Fabry-Perot resonator **42** is designed as follows. A columnar bulk **421** consisting of a first optical material (crystallized quartz in this case) and a columnar bulk **422** consisting of a second optical material (rutile in this case) are bonded to each other in such a manner that their C axes are positioned in the same direction. Dielectric multi-layer films are then respectively deposited on both the end faces of the resultant structure, thus forming reflect filters **423** and **424**.

FIG. **7** shows an enlarged view of the Fabry-Perot resonator **42**. As shown in FIG. **7**, the length of the Fabry-Perot resonator **42** is represented by L. The length L can be represented by the following equation:

$$L=n_{01}l_{01}[1+T\cdot\{\alpha_1+(1/n_{01})\cdot(dn_1/dT)\}]+n_{02}l_{02}[1-+T\cdot\{\alpha_2+(1/n_{02})\cdot(dn_2/dT)\}] \quad (3)$$

where T is a temperature, n_{01} and n_{02} are the refractive indexes of the crystal and the rutile at T=0, dn_1/dT and dn_2/dT are respectively amounts of change in refractive index with respect to the temperatures of the crystallized quartz and rutile, **101** and **102** are respectively the physical lengths of the crystallized quartz and rutile at T=0, and α_1 and α_2 are respectively the linear expansion coefficients of the crystallized quartz and rutile.

In equation (3), if the coefficient part (temperature coefficient) of the temperature T of the crystallized quartz is given as γ_1, and that of the rutile is given as γ_2, the following equation can be established:

$$n_{01}l_{01}\{\alpha_1+(1/n_{01})\cdot(dn_1/di)+n_{02}l_{02}\alpha_2+(1/n_{02})\cdot(dn_2/dT)\}=n_{01}l_{01}\gamma 1+n_{02}l_{02}\gamma 2 \quad (4)$$

If the solution of equation (4) is 0, even if T in equation (3) is changed, the length L is not changed. In order to obtain the temperature coefficients γ_1 and γ_2, the following numbers are substituted into equations (3) and (4):

$$n_{01}=1.53,\ \alpha_1=0.8\times10^{-5},\ dn_1/dT.\ =-7\times10^{-6},$$
$$n_{02}=2.4,\ \alpha_2=0.9\times10^{-5},\ dn_2/dT=-4\times10^{-5}$$

Then, the temperature coefficients γ_1 and γ_2 are given as equations (5) and (6):

$$\gamma_1\simeq3\times10^{-6}/deg \quad (5)$$

$$\gamma_2\simeq8\times10^{-6}/deg \quad (6)$$

Each temperature coefficient is obtained when light is transmitted through the C axis of each optical material. As is apparent from equations (5) and (6), the absolute value of γ_2 is about 2.7 times that of γ_1. Therefore, if the physical lengths **101** and **102** of the optical materials are adjusted to establish the following equation (7), the length L of the Fabry-Perot resonator **42** can be set to be constant with respect to variations in temperature:

$$n_{01}l_{01}:n_{02}l_{02}=2.7:1 \quad (7)$$

In the above embodiment, the two optical materials are bonded to each other such that their C-axis directions coincide with each other. However, these directions need not always coincide with each other. For example, the present invention can be equally applied to a case wherein a rutile bulk as a second optical material and a crystallized quartz bulk as a first optical material are bonded to each other in such a manner that the C axis of the second optical material is perpendicular to that of the first optical material. In this case, if light is polarized in an X direction in FIG. **7**, since

$$n_{02}=2.65,\ \alpha_2=0.7\times10^{-5},\ \text{and}\ dn_2/dT=-4\times10^{-5},$$

the temperature coefficient of the rutile is about -19×10^{-6}/deg. If light is polarized in a γ direction, since

$$n_{n2}=2.65,\ \alpha_2=0.7\times10^{-5},\ \text{and}\ dn_2/dT=-7\times10^{-5},$$

the temperature coefficient of the rutile is about -10×10^{-6}/deg. Therefore, if the ratio of $n_{01}l_{01}$ and $n_{02}l_{02}$ is set to be 6.3:1 when incident light is polarized in the X direction, and the ratio is set to be 3.3:1 when incident light is polarized in the Y direction, the length L of the Fabry-Perot resonator can be kept constant with respect to changes in temperature, thus enabling stable wavelength control of a semiconductor laser.

In the semiconductor laser module having the above-described arrangement, since the Fabry-Perot resonator is constituted by two optical materials having different temperature coefficients, the length of the resonator does not vary with respect to changes in temperature. Hence, the oscillation wavelength of the semiconductor laser can be very stably controlled.

In the above embodiment, crystallized quartz and rutile are used as optical materials constituting the Fabry-Perot resonator. However, the present invention can be applied to a case wherein a Fabry-Perot resonator is constituted by a combination of fused silica and rutile. In addition, if a Fabry-Perot resonator is constituted by a combination of other optical materials having different temperature coefficients, the same effect as described above can be obtained. Furthermore, in the

first and second embodiments, columnar bulks are exemplified. However, the shape of a bulk is not limited to this. For example, the present invention can be applied to a case wherein a hexahedral bulk is used.

In a conventional apparatus, a half reflecting mirror used for a Fabry-Perot resonator consists of a dielectric multilayer film having a packing density of about 0.9. It is known that the wavelength characteristics of this dielectric multilayer film having a packing density of 0.9 shift depending on a humidity in air. In the conventional apparatus, however, a half reflection mirror having such a packing density is considered to be sufficient for a Fabry-Perot resonator for the following reasons:

(1) The characteristics of a Fabry-Perot resonator are given as follows:

$$\beta=4\pi nL\cdot\cos\theta/\lambda$$

$$F=\pi\sqrt{R}/(1-R)$$

where β is a phase difference of the Fabry-Perot resonator, θ is the incident angle of light radiated on the Fabry-Perot resonator, F is the fineness of the Fabry-Perot resonator, and R is the reflectivity of a reflecting mirror. According to these equations, the wavelength axis of the characteristics is influenced by only nL·cos θ and does not depend on a wavelength shift of the multilayer film.

(2) The reflectivity characteristics of a dielectric multilayer film used for the Fabry-Perot resonator are gradually changed with changes in wave-length. Therefore, even if a wavelength shift of the multilayer film occurs due to a humidity change, a change in reflectivity is very small, and no problem is posed.

It was found from high-precision experiments on the above-described points that the refractive index of a dielectric multilayer film constituting a reflecting mirror was changed by 5 to 6% due to the influences of humidity. This changed the phase of a reflected wave, and hence the wavelength characteristics of the resonator shifted. If the wavelength characteristics of the Fabry-Perot resonator shift, the oscillation wavelength of a semiconductor laser using the wavelength of the resonator as a reference wavelength shifts accordingly. Therefore, a stable operation of the Fabry-Perot resonator with respect to humidity cannot be performed. Since humidity is generally associated with temperature, a resonator which has poor humidity stability tends to have poor temperature stability. Since a reflect filter is also constituted by a dielectric multilayer film in the above-described embodiments, the same problems as described above are posed.

FIG. 8 is a view, showing reflect filters consisting of the above-described dielectric multilayer film of a semiconductor laser module according to the third embodiment of the present invention, for explaining a means for stabilizing the wavelength of a semiconductor laser by reducing changes in refractive index due to humidity and suppressing a shift of wave-length characteristics of a resonator.

That is, FIG. 8 shows a Fabry-Perot resonator as a simple model, in which dielectric single-layer films B each having a refractive index n_H and an optical length $l=\pi/4$ are respectively formed on both the end faces of a substance A (air in a conventional apparatus and the crystallized quartz bulk in the first embodiment) having a refractive index n_L and a length L.

The dielectric single-layer film B is porous, and its refractive index nH is given by the following equation:

$$(n_H^2-n_S^2)/(n_H^2+2n_S^2)=(1-P)\{(1-f)(n_V^2-n_S^2)/(n_V^2+2n_S^2)+f(n_W^2-n_S^2)/(n_W^2+2n_S^2)\} \quad (8)$$

where n_S is the refractive index of a thin-film material, n_V is the refractive index of a void (=1), n_W is the refractive index of an absorptive material (=1.33), P is a packing density, and f is the occupation ratio of the absorptive material to the void. As is apparent from equation (8), f is changed with a change in humidity, and n_H is changed with this change. In this case, the thickness of the single-layer film is given is l its wavelength is given as λ, and the refractive index n_H at f=0 is given as n_{H0}, and these factors are set to establish the following equation:

$$l=\lambda/4n_{H0}$$

In FIG. 8, reflected light components a_1 and a_2 will be considered. a_1 and a_2 can be regarded as complex amplitudes of the reflected light components, and the following relation can be established:

$$|a_1|\approx|a_2|=(n_H-n_L)/(n_H+n_L)=a$$

If a_1 and a_2 are obtained in this relation,

$$a_1=ae^{j(\omega t+\pi)} \quad (9)$$

$$a_2=ae^{j(\omega t+2\,nHl\times 2/\lambda)}=ae^{j\{\omega t+\pi(1+\delta)\}} \quad (10)$$

where $n_H/n_{H0}=1+\delta$. According to equations (9) and (10):

$$a_1+a_2=ae^{j(\omega t+\pi)}(1+e^{j\pi\delta})$$

Therefore, as the refractive index n_H of the single-layer film is changed, the phase of a reflected wave is changed by about $\pi\delta/2(|\pi\delta|<<1)$.

As described above, in a Fabry-Perot resonator, a shift of the wavelength characteristics due to a phase deviation of a reflected wave from a reflect filter is more influential than a change in reflection coefficient a by 1%. In the present invention, a wavelength shift of a semiconductor laser due to such a phase shift is considered as an important problem. If a wavelength shift amount is $\partial\lambda$, $\partial\lambda=(\delta/h)\partial h=\lambda^2\delta/4h$ (11)

where h is an effective resonator length. In this case, ti h=nL $\partial h=(\lambda/2\pi)(\pi\delta/2)=\lambda\delta/4$

With the substitution of actual numbers, i.e., h=2 mm, $\lambda=1.5$ μm, and $\delta=0.05$, $\partial\delta$ is 0.14 Å. This corresponds to a variation of 2.5% of a free space spectral interval ($\lambda^2/2h$).

The above-description is associated with a single-layer film. A phase change amount is increased almost in proportion to the number of layers, and a wavelength shift is also increased. In contrast to this, variations in reflection amount due to humidity tend to be suppressed in a multilayer film as compared with a single-layer film, and hence a wavelength shift poses a greater problem. Under the circumstances, in the present invention, each reflect filter of a Fabry-Perot resonator is constituted by a dielectric multilayer film having a packing density of 0.98 or more. As is apparent from equation (8), a change in refractive index due to humidity is reduced with an

increase in packing density. Therefore, a phase change of a reflected wave from the reflect filter can be suppressed with an increase in packing density. With a decrease in length of a Fabry-Perot in particular, the amount of wavelength shift is increased, as is apparent from equation (11). Therefore, such a dielectric multilayer film is very effective for a resonator having a length of 5 mm or less.

If each reflect filter of a Fabry-Perot resonator is constituted by a dielectric multilayer film having a packing density of 0.98 or more, the wavelength characteristics of the resonator can be stabilized, thereby stabilizing the oscillation wavelength of a semiconductor laser in a semiconductor laser wavelength control apparatus incorporating this resonator. In addition, since the humidity is a function of temperature, the stability of the apparatus having the above-described arrangement with respect to temperatures can be improved.

Note that dielectric multilayer films are formed by an electron beam depositing apparatus, a sputtering apparatus, or the like. In order to form a dielectric multilayer film having a high packing density, each apparatus must be improved to some degree. Similar to this embodiment, even if each reflect filter of a Fabry-Perot is constituted by a dielectric multilayer film having a packing density of 0.98 or more in the embodiments shown in FIGS. 5 and 6, the same effect can be obtained.

Instead of using the above-described means for suppressing a shift of the wavelength characteristics of a Fabry-Perot, a means for reducing a change in refractive index of a resonator due to the environmental humidity of the resonator may be considered.

FIG. 9 shows an arrangement of the fourth embodiment of a semiconductor laser module according to the present invention, which is designed to reduce a change in refractive index of the Fabry-Perot resonator due to the environmental humidity of the resonator and to suppress a shift of resonator wavelength characteristics, thereby stabilizing the wavelength of a semiconductor laser. The same reference numerals in FIG. 9 denote the same parts as in FIG. 1, and a description thereof will be omitted.

Reflecting mirrors **191** and **192** of a Fabry-Perot resonator **19** in this embodiment are respectively constituted by dielectric multilayer films. As described above, therefore, the phase of reflected light is changed due to the influences of humidity. As a result, the wavelength characteristics of the Fabry-Perot resonator **19** are shifted. In this embodiment, therefore, in order to air-tightly seal the Fabry-Perot resonator **19**, the entire module is housed in a package **43**. In order to allow radiation of a laser beam S_1 onto an optical fiber **14**, a window **431** is formed at the radiation position of the package **431**. The window **431** consists of, e.g, glass or sapphire, and its peripheral portion is sealed.

In such an arrangement, no moisture enters or escapes from the package **43**, and hence the humidity with respect to the Fabry-Perot resonator **19** is constant. Since a semiconductor laser module generally performs temperature control by using a Peltier element or the like, if the moisture content and temperature in the package **43** are constant, the humidity has a constant value. If, however, no temperature control is performed, constant humidity cannot be set even with a constant moisture content. In such a case, a dry, high-purity inert gas or nitrogen may be sealed in the package **43**.

In the semiconductor laser module having the above-described arrangement, since the humidity with respect to the Fabry-Perot resonator **19** is constant, the refractive indexes of the reflecting mirrors **191** and **192** can be set to be constant. If, therefore, the above-described laser wavelength control apparatus is arranged in this module, the oscillation wavelength of a semiconductor laser **11** can be detected with high precision, and a laser beam having a stable wavelength can be obtained.

In the above embodiment, the present invention is applied to the semiconductor laser module using a general Fabry-Perot resonator. However, the present invention can be equally applied to a semiconductor laser module using a Fabry-Perot resonator consisting of etalon shown in FIGS. 5 and 6. In addition, the package need not necessarily cover the entire module but may be designed to cover only the Fabry-Perot resonator whose humidity change especially influences stability of a wavelength. Furthermore, a better effect can be obtained by combining this embodiment with the third embodiment described with reference to FIG. 8.

FIG. 10 shows an arrangement of the fifth embodiment of a semiconductor laser module according to the present invention, which is designed to reduce a change in refractive index of the above-described Fabry-Perot resonator due to its own humidity and suppress a shift of the resonator wavelength characteristics, thereby stabilizing the wavelength of a semiconductor laser. The same reference numerals in FIG. 10 denote the same parts as in FIG. 5, and a description thereof will be omitted.

A Fabry-Perot resonator **39** consisting of the above-described etalon is designed such that dielectric multilayer films are respectively deposited on both the end faces of a crystal bulk **391** so as to form reflect filters **392** and **393**. In this case, the phase of reflected light is changed when the dielectric multi-layer film is influenced by humidity, and the wavelength characteristics of the Fabry-Perot resonator are shifted. In this embodiment, therefore, in order to air-tightly seal the Fabry-Perot resonator **39**, the resonator is housed in a package **44**. The package **44** is constituted by lids **443** respectively including windows **441** and **442** and a casing **444**. The Fabry-Perot resonator **39** is housed and fixed in the casing **444**. The lids **443** and the casing **444** are sealed together to air-tightly seal the Fabry-Perot resonator **39**. The windows **441** and **442** are formed to allow incidence and emergence of light, and consist of glass, sapphire, or the like. The peripheral portion of each window is sealed.

A characteristic feature of this arrangement will be described below. In the embodiment shown in FIG. 9, if a high-purity gas is filled in the package **43**, the wavelength characteristics upon assembly of the module are shifted. In this embodiment, however, since the Fabry-Perot resonator **39** is housed in the package, and is subsequently attached to the semiconductor laser module, even if the wavelength characteristics of the Fabry-Perot resonator housed in the package **44** are shifted, its wavelength characteristics can be set by only adjusting the incident angle at the time of attachment of the resonator to the semiconductor laser module. According to the arrangement of this embodiment, therefore, in addition to the effect of the embodiment in FIG. 9, another effect can be obtained, i.e., complicated adjustment after assembly of the module can be omitted.

In this embodiment, the Fabry-Perot resonator consisting of etalon is housed in the package. However, this

embodiment can be equally applied to a conventional Fabry-Perot resonator consisting of a pair of reflecting mirrors. In addition, a better effect can be obtained by combining this embodiment with the third embodiment described with reference to FIG. 8.

In the first embodiment shown in FIG. 5, when the reflect filter 392 of the Fabry-Perot resonator 39 is perpendicular to the optical axis of incident light, light which is incident on the Fabry-Perot resonator 39 is reflected by the reflect filter 392 and is returned to the end face of the semiconductor laser 31 or the end face of a sub-mount on which the semiconductor laser 31 is mounted. As a result, the oscillation frequency of the semiconductor laser 31, the intensity of a laser beam, and the like become unstable. As the reflect filter 392 of the Fabry-Perot resonator 39 is inclined with respect to the optical axis, an amount of light which is transmitted through the resonator 39 is decreased, and the fineness is degraded. Therefore, as the inclination angle of the reflect filter 392 is increased, an amount of light which is incident on the photodetector 41 as a frequency detection monitor is decreased, and hence is disadvantageous in terms of wavelength stability.

FIG. 11 shows the sixth embodiment which is designed to solve this problem. The same reference numerals in FIG. 11 denote the same parts as in FIG. 5, and a description thereof will be omitted.

A semiconductor laser 31 is mounted on a sub-mount 46 on a laser system 45. Light S_2 emitted from one side of the semiconductor laser 31 is split by a beam splitter 36. One split light component S_3 is received by a first photodetector 38 through an optical lens 37. The other split light component S_4 is incident on a Fabry-Perot resonator 47 consisting of a crystallized quartz etalon and having substantially the same arrangement as that shown in FIG. 5. Although reflect filters 472 and 473 respectively formed on both the end faces of a crystallized quartz bulk 471 of the Fabry-Perot resonator 47 are parallel to each other, they are not perpendicular to the optical axis of the incident light S_4 and are inclined at a certain angle. The light which is transmitted through the Fabry-Perot resonator 47 is received by a second photodetector 41 through an optical lens 40. Outputs from the first and second photodetectors 38 and 41 are used for control of stabilizing the wavelength of the semiconductor laser 31 through the above-described feedback control.

An operation performed when the reflect filters 472 and 473 of the Fabry-Perot resonator 47 are inclined as in FIG. 11 will be described below with reference to FIG. 12. FIG. 12 shows an enlarged view of the semiconductor laser 31, the optical lens 35, and the reflect filter 472 of the Fabry-Perot resonator 47. For the sake of a simple description, the beam splitter 36 is omitted from FIG. 2.

Referring to FIG. 12, light S_5 reflected by the reflect filter 472 of the Fabry-Perot resonator 47 does not return to the end face of the sub-mount 46 on which the semiconductor laser 31 is mounted because of the inclination of the reflect filter 472 but returns to the module space opposite to the side on which the semiconductor laser 31 is mounted. In this case, an inclination angle θ_1 of the reflect filter 472 with respect to the vertical plane of the optical axis is set as follows:

$$\theta_1 > d_1/2f \quad (12)$$

where d_1 is the distance from the upper surface of the semiconductor laser 31 to an active layer 311 as shown in FIG. 12, and f is the focal length of the optical lens 35. The inclination angle θ_1 is set to be equal to that of the other reflect filter 473 so as to cause the axis of incident and output light components on and from the Fabry-Perot resonator 47 to be parallel to each other.

When the reflect filters 472 and 473 of the Fabry-Perot resonator 47 are inclined at θ_1 as defined by inequality (12), light from the semiconductor laser 31 returns to the module space opposite to the side on which the semiconductor laser 31 is mounted. Therefore, the light does not return to the end face of the semiconductor laser 31 or the end face of the sub-mount 46. In this case, since d_1 is very small, only a small inclination angle θ_1 is required. This prevents a great reduction in amount of light transmitted through the resonator 47 and degradation in fineness. As shown in FIG. 13 (the same reference numerals in FIG. 13 denote the same parts as in FIG. 12, and a description thereof will be omitted), the reflect filters 472 and 473 may be including in the opposite direction to that in FIG. 12. In this case, an inclination angle θ_2 may be set as follow:

$$\theta_2 > d_2/2f \quad (13)$$

where d_2 is the distance from the active layer 311 of the semiconductor laser 31 to the lower surface of the sub-mount 46 as shown in FIG. 13. In this case, light S_5 reflected by the reflecting surface 472 returns to a lower side than the lower surface of the sub-mount 46 but does not return to the end face of the semiconductor laser 31 or the end face of the sub-mount 46.

In the semiconductor module having the above-described arrangement, since the reflect filters of the Fabry-Perot resonator on which a laser beam is incident are properly inclined, reflected light does not return to the end face of the semiconductor laser or the end face of the sub-mount. Therefore, a reduction in amount of transmitted light can be minimized, and stabilization of the wavelength of the semiconductor laser can be realized without degrading the fineness.

Even if the mount position of the semiconductor laser 31 is changed as shown in FIGS. 14 and 15, the reflect filters 472 and 473 of the Fabry-Perot resonator 47 may be inclined on the basis of inequality (12) or (13) so as not to cause the reflected light S_5 to return to the end face of the semiconductor laser 31 or of the sub-mount. Note that in FIGS. 14 and 15, reference numerals 48 and 51 denote module bases; 49 and 52, laser stems; and 50 and 53, sub-mounts.

In the above-described embodiment, the reflect filters 472 and 473 of the Fabry-Perot resonator 47 are inclined. However, the same effect as described above can be obtained by using the Fabry-Perot resonator 39 shown in FIG. 5 without any modification, and including the entire body of the resonator at a predetermined angle. It is apparent that the Fabry-Perot resonator used in this embodiment can have any shape as long as the relation represented by inequality (12) or (13) is satisfied. Therefore, this embodiment can be equally applied to, e.g., a hexahedral Fabry-Perot resonator. In addition, the same effect as described above can be obtained from a combination of the second to fifth embodiments.

FIG. 16 shows a semiconductor laser module and the first embodiment of its laser wavelength control apparatus according to the present invention. FIG. 16 shows an arrangement which is designed to control the oscillation wavelength of the semiconductor laser 31 in the

semiconductor laser module shown in FIG. 5. The same reference numerals in FIG. 16 denote the same parts as in FIG. 15, and only different portions will be described below.

Referring to FIG. 16, a bulk 541 of a Fabry-Perot resonator 54 used in this embodiment is formed into a rectangular parallelepiped shape having square or rectangular end faces, and dielectric multilayer films are respectively deposited on both the end faces (each having a Z-cut surface which is cut in the Z-axis direction (perpendicular to the C-axis direction)) of the bulk 541 so as to form reflect filters 542 and 543. A pair of electrode plates 544 and 545 are attached to a pair of side surfaces (X-cut surfaces cut in the X-axis direction) which are perpendicular to the Z-cut surfaces and are opposite to each other. This pair of electrode plates 544 and 545 are connected to the output terminal of an AC power source 55. With this arrangement, an AC signal V_1 from the AC power source 55 is applied to the electrode plates 544 and 545 so as to apply an electric field E_X in the X-axis direction, thus linearly polarizing incident light S_4 in the X- or Y-axis direction.

An output from a second photodetector 41 is supplied to a synchronous detection unit 56 together with an output from an AC power source 55. The synchronous detection unit 56 serves to perform synchronous detection by multiplying an output V_2 from the second photodetector 41 by an AC input V_1 and removing high-frequency components from the product, and to output the detection result as an error signal to a feedback controller 57. The feedback controller 57 amplifies the input error signal by a predetermined feedback gain and changes an injection current (or temperature) for determining the oscillation wavelength of the semiconductor laser 31 in accordance with the value of the feedback gain, thus controlling the error signal to be zero.

An operation of the semiconductor laser module and its laser wavelength control apparatus having the above-described arrangement will be described with reference to FIG. 17 which shows the wavelength characteristics of an output from each component. Referring to FIG. 17, a solid curve p represents the transmission characteristics of the Fabry-Perot resonator 54 using a crystallized quartz etalon, which have periodic peaks. Assume that the semiconductor laser 31 is oscillated at a wavelength indicated by a point A in FIG. 17. Since the AC signal V_1 having a predetermined frequency is applied to the bulk 541, its transmission characteristics p vary by a small amount, as indicated by a dotted curve p'. Therefore, light S_4 which is incident on the second photodetector 41 through the Fabry-Perot resonator 54 is modulated to light S_4' by transmission characteristics p - p' of the Fabry-Perot resonator 54. If the AC signal V_1 applied to the bulk 541 is given as

$$V_1 = a \cdot \sin \omega t \tag{14}$$

then, an AC component V_2 extracted from the second photodetector 41 is approximately represented by the following equation:

$$V_2 = -C(dp/d\lambda)a \cdot \sin \omega t \tag{15}$$

where C is a proportional constant, and $dp/d\lambda$ is a value obtained by differentiating the solid curve (the transmission characteristics of the bulk 541) p by a wavelength λ.

Since the output V_3 is obtained by calculating the product of the two signals V_1 and V_2 and removing high-frequency components therefrom,

$$\begin{aligned} V_1 \times V_2 &= -C(dp/d\lambda)a^2 \sin^2 \omega t \\ &= -C(dp/d\lambda)(a^2/2)(1 - \cos 2\omega t) \\ \therefore V_3 &= -C(dp/d\lambda)(a^2/2) \end{aligned} \tag{16}$$

That is, the output V_3 from the synchronous detection unit 56 is proportional to the alternate long and dashed curve obtained by differentiating the solid curve p. The feedback controller 57 receives the output after this synchronous detection as the error signal V3, and controls the wavelength λ of the semiconductor laser 31. Therefore, a set wavelength can be matched with the resonance wavelength of the Fabry-Perot resonator 54. As is apparent from FIG. 17 the set wavelength is located at the center of the wavelength capture range. In addition, as is apparent from equation (16), variations in sensitivity of the photodetector 40 and variations in amount of laser beam appear as variations in a and C. However, since the error signal is controlled to set $V_3 = 0$, these variations cause no variation in set wavelength. Therefore, the control apparatus having this arrangement is highly resistant to various types of drifts.

FIG. 18 shows a semiconductor laser module and the second embodiment of its laser wavelength control apparatus according to the present invention, which has an arrangement obtained by improving the laser wavelength control apparatus shown in FIG. 16. The same reference numerals in FIG. 18 denote the same parts as in FIG. 16 and a description thereof will be omitted.

Since the bulk 541 used for the Fabry-Perot resonator 54 shown in FIG. 16 consists of crystallized quartz the bulk may be used as a crystal oscillator. In the embodiment shown in FIG. 18, a pair of electrodes 544 and 545 arranged on a bulk 541 are connected to a feedback circuit 581 so as to constitute a crystal oscillator together with an amplifier 582. In this arrangement, an oscillation signal is extracted from this oscillator and is input to a synchronous detection unit 56 together with an output from a second photodetector 41. According to this arrangement, since the bulk 541 is oscillated, as an oscillator, at a natural resonance frequency, the transmission characteristics of the crystal Fabry-Perot resonator can be effectively oscillated without adjusting a frequency.

In the embodiments shown in FIGS. 16 and 18, if an error signal is obtained by adding a proper offset voltage to an output after synchronous detection, a laser oscillation wavelength can be set near the resonance frequency of the Fabry-Perot resonator 54. In addition, the pair of electrode plates 544 and 545 need not always be attached to a side surface of the bulk 541. For example, these electrodes may be attached to the reflect filters 542 and 543 so that incident light S_4 is linearly polarized in the Y-axis direction upon application of an electric field E_Z in the Z-axis direction. With this arrangement, the same effects as described above can be obtained. According to these embodiments, since a set wavelength is located at the center of the wavelength capture range, a stable feedback operation can be easily performed, and the fineness of the Fabry-Perot resonator can be improved to increase its sensitivity. In addition, since the laser wave-length control apparatus is not easily influenced by drifts of the optical detection

system and the amplifier for amplifying a signal therefrom, and the like, the oscillation wavelength of a laser beam can be stabilized over a long period of time. Therefore, a semiconductor laser apparatus suitable for coherent optical communication and the like can be realized.

A laser wavelength can be further stabilized by combining the laser wavelength control apparatuses of the first and second embodiments with the respective embodiments shown in FIGS. 6, 8, 10, 11, and 13 as well as the embodiment shown in FIG. 5.

In a conventional semiconductor laser module, when a laser wavelength is to be stably controlled, a piezoelectric element is attached to one reflecting mirror of a Fabry-Perot resonator, and an AC signal is applied to the piezoelectric element so as to oscillate the reflecting mirror. Light emitted from the Fabry-Perot resonator, which is changed by this oscillation, is photoelectrically converted, and synchronous detection of the converted signal is performed with respect to the AC signal. A detection signal obtained in this manner is used as an error signal in such a manner that feedback control is performed on the basis of the error signal so as to change the injection current or temperature of the semiconductor laser.

In this arrangement, since the semiconductor module is easily influenced by temperatures as described above, it is generally assembled on a member which is stabilized in terms of temperature by using a Peltier element or the like. However, even with such a countermeasure against the influences of temperatures, the wavelength of the module varies upon influences of changes in external temperature. This is because heat is externally conducted to the piezoelectric element through feeder lines, and the length of the Fabry-Perot resonator varies due to the thermal expansion of the piezoelectric element.

FIG. 19 shows a semiconductor laser module and the third embodiment of its laser wavelength control apparatus according to the present invention, which is designed to solve this problem. In this arrangement, a Fabry-Perot resonator consists of a dielectric crystal having an electro-optic effect, e.g., the crystallized quartz in the above-described embodiments or $LiNbO_3$. That is, the present invention is applied to a case wherein modulation of an optical length is performed by using an electro-optic effect. The same reference numerals in FIG. 19 denote the same parts as in FIG. 16, and only a different part thereof will be described below. For the sake of a simple description, the beam splitter 36, the optical lens 37, and the first photodetector 38 in FIG. 1 are omitted, and the laser wave-length control apparatus in FIG. 16 is employed.

Referring to FIG. 19, a laser beam S_1 emitted from one end of a semiconductor laser 31 is focused on an optical fiber 34 through optical lenses 32 and 33. A laser beam S_2 emitted from the other end of the semiconductor laser 31 is collimated by an optical lens 35 and is then guided to a Fabry-Perot resonator 65. The laser beam S_2 is modulated by the resonator 65 and is received by a photodetector 41 through an optical lens 40.

Similar to the Fabry-Perot resonator shown in FIG. 16, the Fabry-Perot resonator 65 is designed such that dielectric multilayer films are respectively deposited on the opposite surfaces of a rectangular parallelepiped dielectric crystal 651, which are perpendicular to an optical path, so as to form reflecting surfaces 652 and 653, and electrode plates 654 and 655 are attached to opposite parallel surfaces of the crystallized quartz 651. The Fabry-Perot resonator 65 is fixed on a support base 61 which has excellent conductivity and is stabilized in terms of temperature. In this embodiment, in order to prevent the conduction of heat from an AC power source 55 to the Fabry-Perot resonator 65 through feeder lines 631 and 632, the

First and second insulating pads 661 and 662 having excellent heat conductivity are formed on the support base 61. One feeder line 631 from the AC power source 55 is connected to a first pad 661 through a feeder line 633 having high heat resistance. The first pad 661 and a second pad 662, and the second pads 662 and one electrode plate 654 of the Fabry-Perot resonator 65 are respectively connected to each other through feeder lines 671 and 672 having high heat resistance. As a result, the feeder line 631 is connected to the electrode 654. The other feeder line 632 (on the GND side) from the AC power source 55 is connected to the lower portion of the support base 61 through a feeder line 634 having high heat resistance. The upper portion of the support base 61 is directly connected to the electrode plate 655 of the Fabry-Perot resonator 65.

According to the above-described arrangement, a change in external temperature which is conducted through the feeder line 631 located outside the module is absorbed by the support base 61 through the first and second insulating pads 661 and 662. A change in external temperature which is conducted through the feeder line 631 is directly absorbed by the support base 61. Since the feeder lines 671 to 672 and 633 to 634 have high heat resistance, the Fabry-Perot resonator 65 is thermally isolated from the outside perfectly. Therefore, the semiconductor laser 31 and the Fabry-Perot resonator 65 are free from the influences of external temperatures, and especially variations in length of the Fabry-Perot resonator 65 due to temperatures can be prevented. This enables stable wave-length control. In addition, if a plurality of pads or wire members having high heat resistance are used and the GND side of the AC channel is directly fixed to a temperature-stabilizing member, temperature stability can be further improved.

More stable laser wavelength control can be performed by combining the arrangements of the fourth and fifth embodiments with the arrangements shown in FIGS. 6, 8, 9, 10 and 13.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, and representative devices, shown and described herein. Accordingly, various modifications may by without departing from the spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.

What is claimed is:

1. An apparatus for controlling the oscillation wavelength of a laser, comprising:

a semiconductor laser emitting a laser beam;

a Fabry-Perot resonator receiving said emitted laser beam including a crystallized quartz bulk having two flat surfaces which are perpendicular to a C-axis direction and parallel and opposite to each other, said Fabry-Perot resonator being provided with dielectric multi layer films respectively deposited on the flat surfaces so as to form reflect filters which enable stable wavelength control, and said crystallized quartz bulk being on an optical axis of one of said laser beams emitted from said semicon-

ductor laser so that the C-axis direction is parallel to the optical axis of said semiconductor laser, thereby detecting a wavelength of incident light; and

a photodetector receiving and photoelectrically converting light which is transmitted through said Fabry-Perot resonator to produce a signal connected to said semiconductor laser, thereby controlling the wavelength of said semiconductor laser.

2. An apparatus according to claim 1, wherein each of the dielectric multilayer films of said Fabry-Perot resonator has a packing density of not less than 0.98.

3. An apparatus according to claim 1, further comprising a package for storing and air-tightly sealing at least said semiconductor laser and said Fabry-Perot resonator.

4. An apparatus according to claim 3, wherein a high-purity inert gas is sealed in said package.

5. An apparatus according to claim 4, wherein the inert gas consists of nitrogen

6. An apparatus according to claim 1, further comprising a package for storing and air-tightly sealing said Fabry-Perot resonator.

7. An apparatus according to claim 6, wherein a high-purity inert gas is sealed in said package.

8. An apparatus according to claim 6, wherein the inert gas consists of nitrogen.

9. An apparatus according to claim 1, wherein said Fabry-Perot resonator is inclined with respect to an optical axis of incident light so as to deflect light, which is reflected by an incident side reflect filter, in an opposite direction toward a side on which said semiconductor laser is mounted while preventing incidence of the reflected light on a radiation surface of said semiconductor laser.

10. An apparatus according to claim 1, wherein said photodetector is a first photodetector and said apparatus further comprises:

light splitting means splitting a laser beam emitted from said semiconductor laser to said Fabry-Perot resonator;

a second photodetector receiving and photoelectrically converting a laser beam split by said light splitting means; and

a feedback controller for detecting a level difference between detection signals output from said first and second photodetectors, generating a detection signal as an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

11. An apparatus according to claim 1, wherein said Fabry-Perot resonator is formed into a rectangular parallelepiped shape and comprises electrode plates respectively attached to a pair of surfaces parallel to the C axis, and said semiconductor laser apparatus further comprises:

an AC power source for applying an AC signal to the electrode plates of said Fabry-Perot resonator;

a synchronous detection circuit performing synchronous detection of a detection signal output from said photodetector receiving and photoelectrically converting a laser beam which is transmitted through said Fabry-Perot resonator on the basis of the AC signal output from said AC power source; and

a feedback controller identifying a detection signal from said synchronous detection circuit with an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

12. An apparatus according to claim 11, further comprising connecting means, having not less than one electrode pad whose temperature is stabilized, for connecting the electrode plates of said Fabry-Perot resonator to said AC power source through the electrode pads

13. An apparatus according to claim 12, wherein said connecting means uses wire members for feeder lines for connecting said pads to said electrode plates, said wire members being higher in heat resistance than wire members for feeder lines for connecting said pads to said AC power source.

14. An apparatus according to claim 1, wherein said Fabry-Perot resonator is formed into a rectangular parallelepiped shape and comprises electrode plates attached to a pair of surfaces parallel to the C axis and said semiconductor laser apparatus further comprises:

a synchronous detection circuit, connected to the electrode plates of said Fabry-Perot resonator and constituting an oscillation circuit having the crystallized quartz bulk as an oscillator, performing synchronous detection of a detection signal output from said photodetector receiving and photoelectrically converting a laser beam which is transmitted through said Fabry-Perot resonator on the basis of an oscillation signal generated by said oscillation circuit; and

a feedback controller identifying a detection signal from said synchronous detection circuit with an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

15. An apparatus for controlling the oscillation wavelength of a laser, comprising:

a semiconductor laser emitting a laser beam;

a Fabry-Perot resonator receiving said emitted laser beam and having two types bulk having different temperature coefficients bonded to each other and formed into a bulk assembly by dielectric multilayer films being respectively deposited on two flat surfaces of said bulk assembly, which are parallel and opposite to each through bonding surfaces of said bulks, thereby forming reflect filters which enables stable wavelength control, said bulk assembly being on an optical axis of one of said laser beams emitted from said semiconductor laser so that the flat surfaces are perpendicular to the optical axis of said semiconductor laser, thereby detecting a wavelength of incident light; and

a photodetector receiving and photoelectrically converting light which is transmitted through said Fabry-Perot resonator to produce a signal connected to said semiconductor laser, thereby controlling the wavelength of said semiconductor laser.

16. An apparatus according to claim 15, wherein one of the bulks of said Fabry-Perot resonator consists of crystallized quartz and the other bulk consists of rutile.

17. An apparatus according to claim 15, wherein one of the bulks of said Fabry-Perot resonator consists of fused silica and the other bulk consists of rutile.

18. An apparatus according to claim 15, wherein each of the dielectric multilayer films of said Fabry-Perot resonator has a packing density of not less than 0.90.

19. An apparatus according to claim 15, further comprising a package for storing and air-tightly sealing at

least said semiconductor laser and said Fabry-Perot resonator.

20. An apparatus according to claim 19, wherein a high-purity inert gas is sealed in said package.

21. An apparatus according to claim 20, wherein the inert gas consists of nitrogen.

22. An apparatus according to claim 15, further comprising a package for storing and air-tightly sealing said Fabry-Perot resonator.

23. An apparatus according to claim 22, wherein a high-purity inert gas is sealed in said package.

24. An apparatus according to claim 22, wherein the inert gas consists of nitrogen

25. An apparatus according to claim 15, wherein said Fabry-Perot resonator is inclined with respect to an optical axis of incident light so as to deflect light, which is reflected by an incident side reflect filter, in an opposite direction toward a side on which said semiconductor laser is mounted while preventing incidence of the reflected light on a radiation surface of said semiconductor laser.

26. An apparatus according to claim 15, wherein said photodetector is a first photodetector and said apparatus further comprises:

light splitting means splitting a laser beam emitted from said semiconductor laser to said Fabry-Perot resonator;

a second photodetector receiving and photoelectrically converting a laser beam split by said light splitting means; and

a feedback controller detecting a level difference between detection signals output from said first and second photodetectors, generating a detection signal as an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

27. An apparatus according to claim 15, wherein said Fabry-perot resonator is formed into a rectangular parallelepiped shape and comprises a pair of electrode plates respectively attached to opposite surfaces of said rectangular parallelepiped shape, and said semiconductor laser apparatus further comprises:

an AC power source applying an AC signal to the pair of electrode plates of said Fabry-Perot resonator;

a synchronous detection circuit performing synchronous detection of a detection signal output from said photodetector receiving and photoelectrically converting a laser beam which is transmitted through said Fabry-perot resonator; on the basis of the AC signal output from said AC power source; and

a feedback controller identifying a detection signal from said synchronous detection circuit with an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

28. An apparatus according to claim 27, further comprising connecting means, having not less than one electrode pad whose temperature is stabilized, connecting the pair of electrode plates of said Fabry-Perot resonator to said AC power source through the electrode pads.

29. An apparatus according to claim 28, wherein said connecting means uses wire members for feeder lines connecting said pads to said electrode plates, said wire members being higher in heat resistance than wire members for feeder lines for connecting said pads to said AC power source.

30. An apparatus according to claim 15, wherein said Fabry-Perot resonator is formed into a rectangular parallelepiped shape and comprises a pair of electrode plates attached to opposite surfaces of said rectangular parallelepiped shape, and said semiconductor laser apparatus further comprises:

a synchronous detection circuit, connected to the pair of electrode plates of said Fabry-Perot resonator and constituting an oscillation circuit having the crystallized quartz bulk as an oscillator, performing synchronous detection of a detection signal output from said photodetector receiving and photoelectrically converting a laser beam which is transmitted through said Fabry Perot resonator on the basis of an oscillation signal generated by said oscillation circuit; and

a feedback controller for identifying a detection signal from said synchronous detection circuit with an error signal, and controlling an oscillation wavelength of said semiconductor laser so as to decrease the error signal.

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